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Direct shear characteristics of cement stabilized clay subjected to previous shear

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ABSTRACT

The cement stabilization techniques have been applied to various types of infrastructure and become one of the essential techniques. A lot of researches have been conducted on the physical and mechanical properties of the cement stabilized soils, many of which are the studies on the stabilized soil after the hydration. However, the number of researches is limited on the physical and mechanical behavior of cement stabilized soil during the hydration stage and subjected to shear deformation during the hydration stage. In this study, a series of direct shear tests was conducted on the shear behavior of cement stabilized soil to investigate the influence of the magnitude and timing of the shearing on the shear behavior. The researche revealed that the shear strength of the stabilized soil is recovered to the peak strength when it is subjected to the shear deformation prior to the peak strength and the shear strength increases by the cement hydration. On the other hand, when the soil is subjected to the large deformation exceeding to the peak strength, the shear strength loss is not recovered in the following shearing stage. The strength gain due to the cement hydration is also influenced by the initial shearing, where the strength of soil subjected to the large shearing remains small for the curing stage. In this manuscript, the test results are introduced to discuss the influence of the initial shearing as well as the testing procedure.

Keywords: Cement stabilization; Direct shear test; Shear strength; Strength recovery

1. Introduction

The cement stabilization techniques have been applied to various types of infrastructure to improve the stability, reinforce foundation, decrease ground settlement, prevent liquefaction, etc. and becomes one of the essential techniques. The strength gain is enhanced by the cement hydration in the early stage and then by the pozzolanic reaction. A lot of researches have been conducted on the physical and mechanical properties of cement stabilized soils, many of which focus on the fully hydrated stabilized soil (e.g. Kitazume, 2016, JCA, 2017). However, the number of researches is limited on the physical and mechanical behavior of cement stabilized soil during the hydration stage and subjected to shear history during then (e.g. Suzuki *et al*., 2004).

In this study, a series of direct shear tests was conducted on the shear behavior of cement stabilized soil to investigate the influence of the magnitude and timing of the shearing during the hydration stage on the shear behavior of fully hydrated stabilized soil. The Kaolin clay was stabilized by the ordinal Portland cement, and cured and tested at serval curing periods to study the effect of the curing period on the shear behavior. Some of them were subjected to various magnitudes of shear load, 80% of the peak strength, peak strength, 80% and 50% of peak strength in the residual stage.

The researche revealed that the shear strength of the stabilized soil is recovered to the peak strength when it is subjected to the shear deformation prior to the peak strength and the shear strength increases further by the cement hydration. On the other hand, when the stabilized soil is subjected to the large deformation exceeding to the peak strength, the shear strength loss can not be recovered in the following shearing. The strength gain due to the cement hydration is also influenced by the initial shearing during the hydration stage, where the strength of stabilized soil subjected to the large shearing remains small for the curing stage.

In this manuscript, the test results are introduced to discuss the effect of the initial shearing as well as the testing procedure.

2. Direct shear tests

2.1. Preparation of specimen

A soil and cement used in this study are Kaolin clay, *Gs* of 2.63, w_p of 82.1% and w_l of 34.7%, and ordinal Portland cement. The stabilized soil is created according the Japanese Standard (JGS T 0821-2009), where the Kaolin clay is mixed with tap water to make a clay slurry of 100% in the water content, and the clay was stabilized with the cement with 10%, dry weight ratio of cement and soil. The stabilized soil slurry was poured into a plastic mould by the tapping technique to create plate of 60 mm in diameter and 20 mm in height, as shown in Figure 1. The surface of stabilized soil in the mould was lapped with vinyl sheet in order to prevent drying and cured in a controlled chamber, 20 degree and 100% in relative humidity.

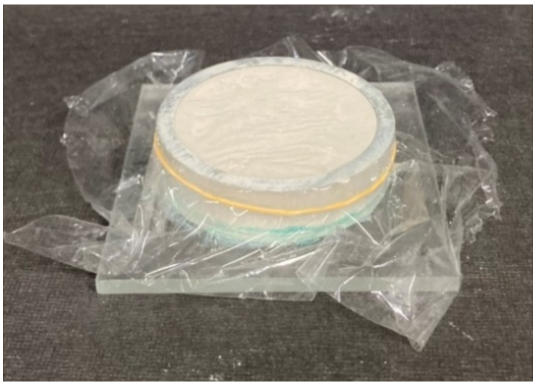


Figure 1. Cement stabilized soil in the plastic mold, diameter and height of which are 60 mm and 20 mm respectively.

2.2. Direct shear testing procedure

After curing, the stabilized soil in the mould was taken out and set in the direct shear box. The direct shear test was carried out according to the JGS standard (JGS 0560-2020) as shown in Figure 2, in which the horizontal loading speed was 0.1 mm/min and the vertical stress was 100 kPa. As the loading speed is high, it can be assumed that the shear loading was completed under an undrained condition. The direct shear test was carried out at the curing period of 3, 7, 14 and 28 days. Some specimens were subjected to the shearing to the shear stress of 80% of the peak strength, the peak strength, or the residual stage of 80% or 50% of the peak strength at 3, 7 or 14 days (1st shearing), after the shearing the specimen was cured in the direct shear box to the prescribed curing period and subjected to the 2nd shearing. After the shearing, the specimen was taken out of the direct shear box to observe the shear failure behavior and measure the water content of the specimen.

Figure 2. Direct shear apparatus and shear boxes on the lower table.

3. Test results and discussions

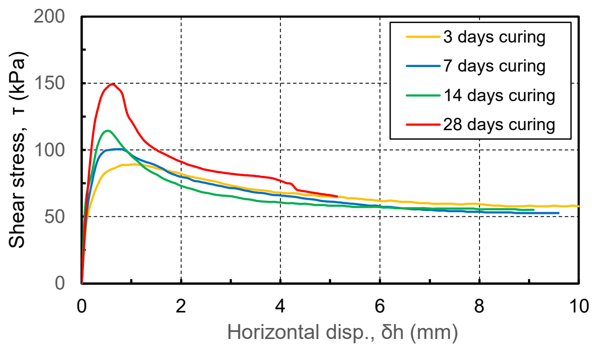
3.1. Intact specimen without the 1st shearing

3.1.1. Shear stress and horizontal displacement relation

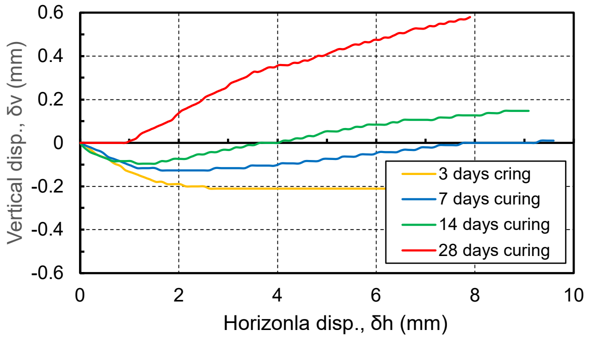
Figure 3(a) shows an example of the shear stress and horizontal displacement relation on the specimen without the 1st shearing (call “intact specimen”) at 3, 7, 14 and 28 curing period. In the case of 3 days curing, the shear stress increases rapidly with the horizontal displacement to reach the peak strength of about 80 kPa at the horizontal displacement of about 1 mm, after the peak strength the shear stress decreases gradually with further loading to the residual stage of about 50 kPa. Similar stress and displacement relation can be seen on the specimen with the longer curing period, but the peak strength increase and the horizontal displacement at the peak strength decreases, the shear stress decreases rapidly, and the shape of shear stress and horizontal displacement curve at around the peak strength becomes more sharply bended. The shear stress decreases rapidly with the horizontal displacement for the longer curing specimen. But the residual strength is almost the same value of about 50 kPa irrespective of the curing period.

Figure 3(b) shows the vertical displacement and horizontal displacement curves of the intact sample for various curing periods. In the case of 3 days curing, the negative vertical displacement can be seen throughout the shearing, which indicates the compressive deformation of about 1% of thickness of specimen takes place. As the curing period becomes longer, the negative displacement (compressive behavior) can be seen at the beginning but the positive displacement (expansive behavior) can be seen at around and after the peak strength. In the case of 14 days curing, the positive deformation (expansive behavior) can be seen in the residual stage. In the case of 28 days curing, the only expansive behavior can be seen throughout the shearing. The large expansive deformation after the peak strength can contribute the rapid and large decrease in the shear stress after the peak, as already shown in Figure 3(a), which is very similar behavior to that of an over-consolidated soil.

Figure 4 shows the relationship between the peak shear strength with the curing period. Though there are a lot of scatter in the data, the peak shear strength increases rapidly with the curing period at first and then gradually, which is very similar test results to previous tests (e.g. Tsuchida *et al.*, 2013).



(a) Shear stress and horizontal displacement relationship



(b) Vertical displacement and horizontal displacement relationship

Figure 3. Shear behavior of intact samples cured at 3, 7, 14 and 28 days.

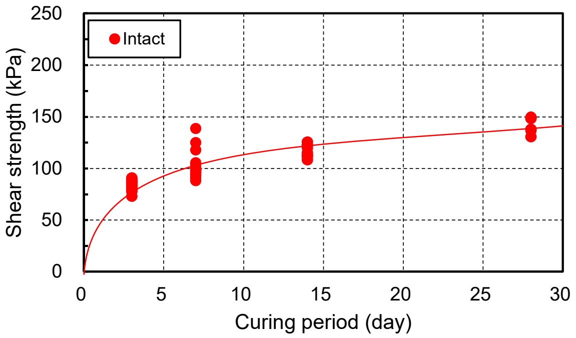


Figure 4. Shear strength and curing period relationship of intact sample.

Figure 5 shows the relationship between the horizontal displacement at the peak strength and curing day, in which the average, minimum and maximum test results are plotted. Though there is a lot of scatter in the test data, the horizontal displacement at the peak strength becomes small gradually with the curing period. The horizontal displacement at the peak strength for the long curing day is quite small of the order of about 0.5 mm, which is less than 1% of the specimen diameter.

Figure 6 shows the relationship between the elastic stiffness and the curing period, where the elastic stiffness is calculated the shear stress increment vs the horizontal displacement at the beginning of loading stage. Through there is a lot of scatter, the stiffness remains almost constant before the 14 days curing, but increases gradually with the curing period.

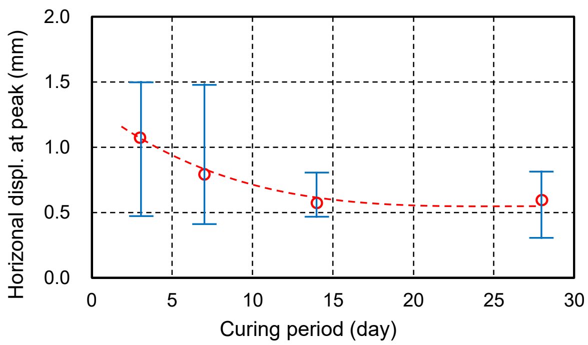


Figure 5. Horizontal displacement at peak strength and curing period relationship on intact specimen.

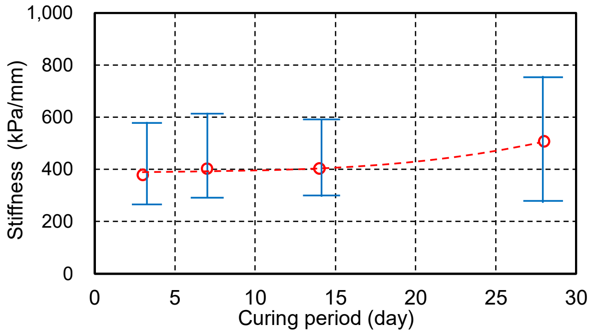


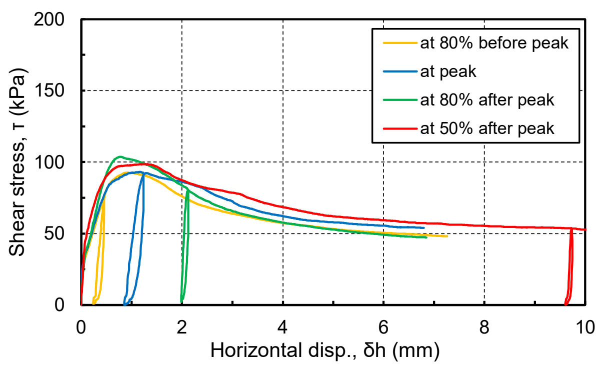
Figure 6. Elastic stiffness and curing period relationship on intact specimen.

These test results indicate that the stabilized soil becomes more brittle characteristics with the curing with large peak strength and stiffness and rapid strength decrease after the peak strength.

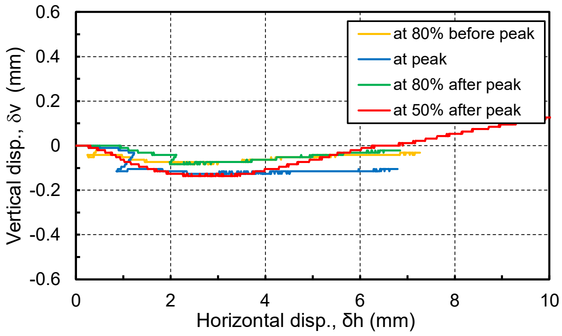
3.1.2. Effect of cyclic shear loading

Some specimens were subjected to the cyclic shear loading at either the 80% of the peak strength, the peak strength, the residual strength of 80% and 50% of the peak strength. The test results are shown in Figure 7. In the case of cyclic shearing at the 80% of the peak strength, Figure 7(a), the shear stress increases very rapidly and increases to the peak strength that is followed by the gradual stress decrease to the residual stage. In the case of the cyclic shearing to the peak strength, the shar stress increases very rapidly to the same strength as the previous level. The peak strength in the reloading stage is almost the same value irrespective of the magnitude of the previous shearing. In the case where the cyclic shearing to the residual stage, the shear stress increases rapidly to the previous level but not to the peak strength, which indicates that the shear stress lost after the peak strength does not recover in the reloading stage. The residual strength after the large deformation is almost the same value irrespective of the magnitude of cyclic shearing.

Figure 7(b) shows the relationship between the vertical displacement and the horizontal displacement in the cyclic shearing. The compressive phenomenon can be seen in the beginning of shearing in all the specimen, the compressive deformation was gradually accumulated by the cyclic shearing but the compression and expansive behavior is not so influenced by the cyclic shearing.



(a) Shear stress and horizontal displacement relationship



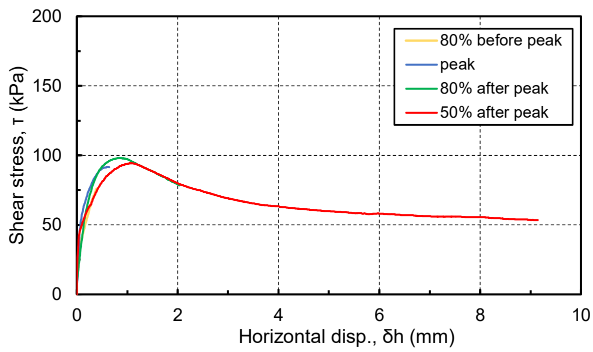
(b) Vertical displacement and horizontal displacement relationship

Figure 7. Effect of cyclic shear loading on the shear behavior of intact specimen.

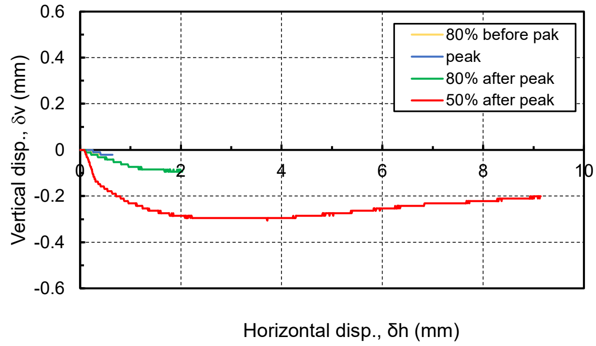
3.1.3. Shear failure plane characteristic

Six pasta of about 3 mm in diameter were installed vertically at about 10 mm interval in some specimen in the preparation of specimen in order to observe the shear failure development during the shearing. At 28 days curing, the four specimens were subjected to the direct shear and terminated at 80% of the expected peak strength, at the peak strength, at 80% and 50% residual strength of the peak strength. Figure 8 shows the shear stress and the vertical displacement along the horizontal displacement. As shown in Figure 8(a), the shear stress and the horizontal displacement show almost the same curve except at the beginning. But the vertical displacement shown in Figure 8(b) also shows the same curve except the case of shearing to 50% of the peak strength.

After the shearing to the prescribed displacement, the specimen was trimmed to dispose the vertical plane of the specimen and shown in Figure 9. As the specimen in Figure 9 is not the same, the position of the pasta are not the same in the specimen. At the 80% of the expected peak strength, Figure 9(a), the line of pasta is not deformed and tilting as the horizontal displacement is quite small. At the peak strength, Figure 9(b), the line of pasta inclined counterclockwise but clear shear failure plane can not be found. At the residual strength, Figure 9(c), relatively large inclination can be seen in the pasta. A clear shear can be found in the two edge pasta, while the two center pasta is not sheared. At the residual strength, 50%, Figure 9(d), the specimen was spread out top and bottom during the remolding, all the four pasta have been spread to show a clear shear failure plane was developed, which is similar to the clay sample (Kamei and Miyata, 1993).



(a) Shear stress and horizontal displacement relationship



(c) Vertical displacement and horizontal displacement relationship

Figure 8. Shear behavior of intact samples for observing failure plane at 28 days.

(a) at 80% of peak strength, (0.39mm of horizontal displacement)

(b) at peak strength, (0.64 mm of horizontal displacement)

(c) at 80% of peak strength in residual stage, (2.03 mm of horizontal displacement)

(d) at 50% of peak strength in residual stage, (9.14 mm of horizontal displacement)

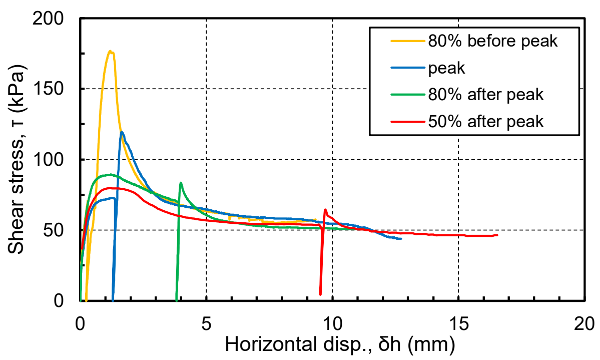
Figure 9. Sectional view of direct shear specimen.

3.2. Effect of first shearing on shear behavior (Effect of magnitude of shear loading)

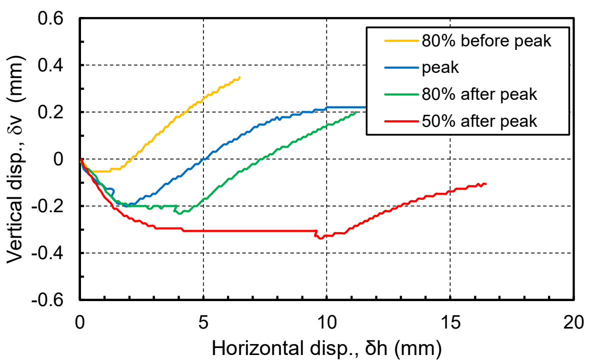
The shear stress and horizontal displacement curve measured in the 2nd shearing at 28 days after the 1st shearing at 3 days is shown in Figure 10(a). The shear stress increases very rapidly to the peak strength at about 1.2 mm in horizontal displacement. The magnitude of the peak strength is about twice of the shear stress in the 1st shearing. In the case of the 1st shearing to the peak strength, the shear stress increases very rapidly in the 2nd shearing to show the large and clear peak strength which is followed by the quick decrease in the shear stress to the residual stage. In the case of the residual stage in the 1st shearing, on the other hand, the shear stress increases rapidly in the 2nd shearing to the peak strength that is lower than the peak strength in the 1st shearing. After the peak strength, the shear stress decreases the residual strength that is the same irrespective of the magnitude of the 1st shear.

Figure 10(b) shows the vertical displacement and the horizontal displacement in the shear stage. The compressive behavior can be seen in the 1st shearing but large expansive behavior can be seen after the peak strength in the 2nd shearing stage. The similar phenomenon can be seen in the case where the 1st shearing to the peak strength and the residual strength stage.

Similar phenomenon can be seen in the case where the specimen was sheared to the peak strength and the residual stage in the 1st shearing.



(a) Shear stress and horizontal displacement relationship



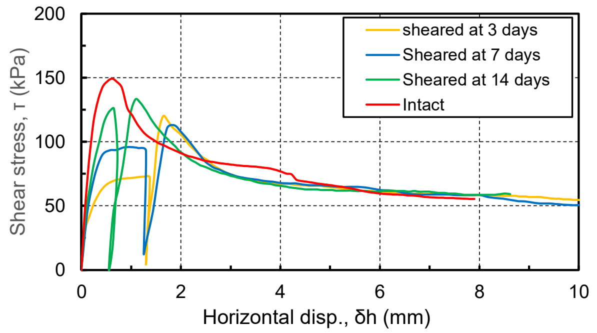
(b) Vertical displacement and horizontal displacement relationship

Figure 10. Effect of first shearing on shear behavior of sample at 28 days curing.

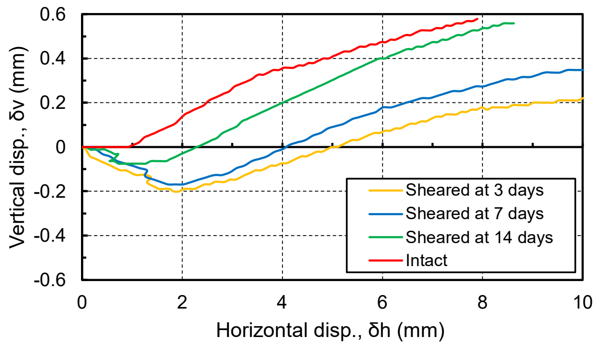
3.3. Effect of first shearing on shear behavior (Effect of timing of shear loading)

Figure 11 shows the shear stress and displacement curves at 28 days that were subjected to the 1st shearing of the peak strength at 3, 7 and 14 days. The shear stress increases rapidly to the clear peak strength in the 2nd shearing, irrespective of the day of the 1st shearing. In the cases of the 1st shearing at 3 and 7 days, the peak strength in the 2nd shearing is larger than that of the 1st shearing, and they show a clear peak curve. But the residual strength in the 2nd shearing is almost the same irrespective of the day of the 1st shearing.

The vertical displacement in the 2nd shearing, Figure 11(b), shows the compressive deformation in the 1st shearing but the expansive deformation after the peak strength in the 2nd shearing. This phenomenon is more dominant for the longer curing in the 1st shearing.



(a) Shear stress and horizontal displacement relationship



(b) Vertical displacement and horizontal displacement relationship

Figure 11. Effect of first shearing on shear behavior of sample at 28 days curing.

Figure 12 replots Figure 5 that shows the horizontal displacement at the peak strength together with those of the 2nd shearing test data. The displacement at the peak in the 2nd shearing is the lowest of the range of those of the 1st shearing.

Figure 13 replots Figure 6 that shows the stiffness together with those of the 2nd shearing test data. The stiffness of the specimen subjected to the 1st shearing at 3 days and the 2nd shearing at 7 and 14 days, shows very large stiffness that that of the 1st shearing, however, shows smaller stiffness than the 1st shearing. Though there is a large scatter in the test data, the stiffness of the specimen subjected to the 1st shearing shows a little bit larger stiffness that that of the 1st shearing but shows almost the same order to the 1st shearing at 28 days.

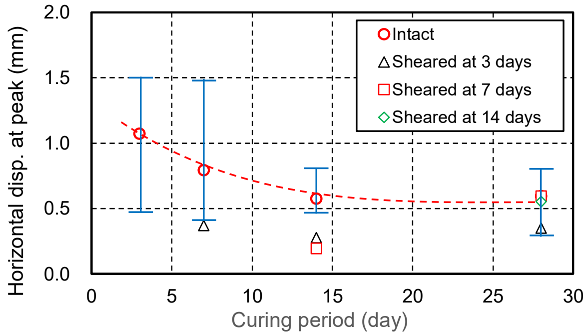


Figure 12. Horizontal displacement at peak strength and curing period relationship on intact specimen.

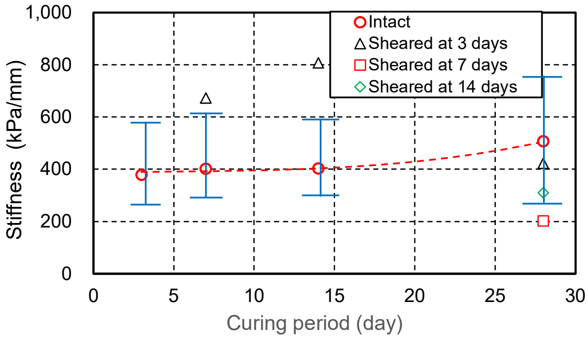


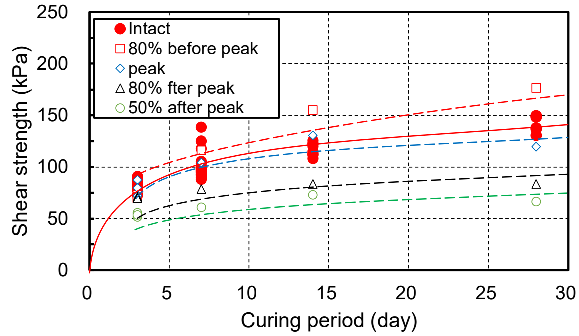
Figure 13. Elastic stiffness and curing period relationship on intact specimen.

3.4. Shear strength gain of stabilized soil subjected to the first shearing

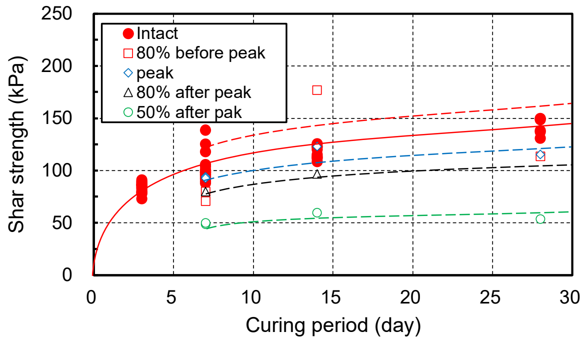
Figure 14 summarizes the test data together with the intact specimen and ones with the 1st and 2nd shearing. In the case of the 1st shearing at 3 days, Figure 14(a), the sample subjected to the 1st shearing up to 80% peak strength increases with the curing period and shows very large strength than that of the intact specimen. The sample subjected to the peak strength in the 1st shearing also increases in the strength and shows the almost same peak strength as the intact specimen. It may come from the scatter of specimen and the same order of the 1st shearing. In the case where the specimen is subjected to the peak strength in the 1st shearing, the specimen shows large shear strength with the curing period.

In the case of the soil subjected to the residual stage in the 1st shearing, the shear strength in the 2nd shearing slightly increase with the curing time, but remains quite small value, smaller than that of the intact specimen. Figures 14(b) and 14(c) show the test results subjected to the 1st shearing at 7 and 14 days respectively, which show a similar phenomenon to Figure 14(a), where the shear strength increases with the curing period irrespective of the timing at the 1st shearing but the strength increment is small when subjecting the residual stage in the 1st shearing. In the case of subjecting up to the peak strength in the 1st shearing shows almost the same strength in the 2nd shearing irrespective of the timing of the 1st shearing.

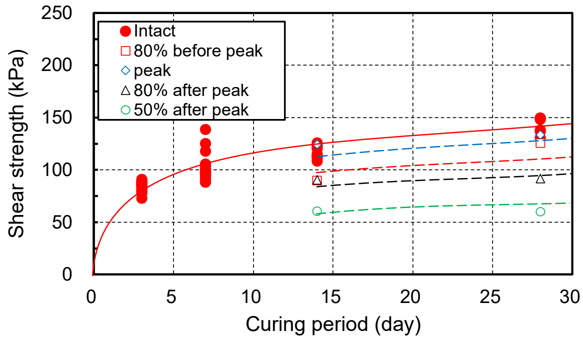
However, in the case subjecting to the 1st shearing at 14 days, the specimen show the increase in the shearing strength in the 2nd shearing stage but the strength increase in the 1st shearing up to the peak strength is smaller than the intact specimen. It can be seen that the strength increment in the 2nd shearing is influenced by the magnitude and the timing of the 1st shearing.



(a) Secimen subjected to first shearing at 3 days curing



(b) Secimen subjected to first shearing at 7 days curing



(c) Secimen subjected to first shearing at 14 days curing

Figure 14. Shear strength and curing period relationship of intact sample.

Figure 15 shows the strength gain from 3, 7 and 14 days to the 28 days. The average of the strength gain is shows for the intact soil in the figure. In the case of the specimen subjected to the 80% and the peak strength in the 1st shearing, the strength gain in the 2nd shearing is almost the same as or larger than that on the intact specimen, which came from the strength recover as shown in Figure 7 and the cement hydration effect. It is quite difficult to identify the cement hydration component from the test data, but it can be said that the strength gain due to the cement hydration is not influenced by the 1st shearing.

In the case of the specimen subjected to the shearing to the residual stage, the strength gain is quite smaller than that of the intact specimen. As shown in Figure 7, the strength loss by the residual shearing can not be recovered, the strength gain shown in Figure 15 can be the cement hydration effect alone, which indicates that the strength gain due to the cement hydration is also influenced by the mechanical disturbance in the 1st shearing.

As the number of specimen was not so large by the limitation of the shear box in the direct shear apparatus, it is hard to discuss the evaluation of the test data quantitively. A large number of specimen box and comprehensive test program is necessary to discuss the test results so detail and quantitively.

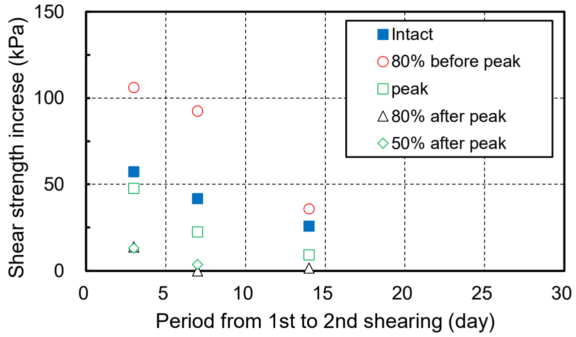


Figure 15. Shear strength gain and curing period relationship.

4. Conclusions

In this study, a series of direct shear tests was conducted on the shear behavior of cement stabilized soil to investigate the influence of the magnitude and timing of the shear on the shear behavior. Major conclusions derived in this study are summarized as follow:

(1) The shear strength of cement stabilized soil increases with the curing period. The shear behavior of stabilized soil becomes from ductile to brittle characteristic with the large strength and small horizontal displacement at he peak strength and quick decrease in shear strength after the peak.

(2) The shear strength of the stabilized soil is recovered to the peak strength when it is subjected to the shear deformation prior to the peak strength and the shear strength increases by the cement hydration.

(3) When the specimen is subjected to the large deformation exceeding to the peak strength, the shear strength loss is not recovered in the following shear.

(4) The strength gain due to the cement hydration is also influenced by the initial shearing, where the strength of specimen subjected to the large shearing remains small for the curing stage.

(5) The shear plane is developed from the edge of specimen.

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