Shear strength-related properties of clayey soil mixed with converter steelmaking slag under overburden pressure for short-time curing

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ABSTRACT

The mixture of clayey soil and steelmaking slag has the property of solidification, where the mixture is consolidated as it solidifies. This study examines the effects of the consolidation of the mixture owing to overburden pressure during curing on properties of its shear strength. A unconfined compression test and a consolidated-undrained triaxial compression test (CU test) were performed on specimens that had been cured while applying an overburden pressure to clayey soil mixed with steelmaking slag. The results of the unconfined compression test revealed that the relationship between overburden pressure and $q_s$ at the same duration of curing was linear, and both the slope and intercept of the primary equation increased with the duration of curing. The CU test showed that an overburden pressure of 50 kN/m² during curing increased the value of $q_{\text{max}}$ by 2.7 times when the mixture was cured under atmospheric pressure for 28 days. In addition, regardless of the presence of overburden pressure during curing, as solidification progressed, a peak appeared in the $q-p’$ plane beyond $q/p’=3$.

Keywords: clayey soil, steelmaking slag, overburden pressure, solidification

1 INTRODUCTION

The mixture of dredged soil and steelmaking slag solidifies due to the reaction between the components of silica and alumina in the former with those of calcium in the latter. Past research (Kakihara et al., 2018, Toda et al., 2018) has shown that the development in the strength of the mixture varies according to differences in components in the clayey soil. When the shear strength of the mixture after being cured for a short duration is low, its consolidation occurs owing to overburden pressure. The mixture is thus consolidated and solidifies simultaneously. However, the shear strength of mixtures of clayey soil and steelmaking slag is conventionally measured once they have been cured in atmospheric pressure. Thus, the effects of the consolidation of the mixture owing to overburden pressure on properties of its shear strength remain unclear.

This study examines the effects of the consolidation of the mixture owing to overburden pressure during curing on properties of its shear strength. Specimens containing clayey soil, consisting mainly of kaolin clay, and converter steelmaking slag were cured for 0.21–28 days under multiple overburden pressures, including atmospheric pressure and a pressure of 50 kN/m². The specimens were consolidated in one dimension owing to overburden pressure. After curing, unconfined compression tests and consolidated-undrained triaxial compression tests were conducted on them.

2 PREVIOUS RESEARCH

In Japan, dredged soil mixed with steelmaking slag is used as a solidifying geo-material. In 2016, the Technology Manual for Use at Port, Airport, and Coast (Coastal Development Institute of Technology, 2017) was published. According to it, it is necessary to conduct mixing tests on the dredged soil and steelmaking slag used because it is difficult to stably develop the shear strength of the mixture. When the attained shear strength is different from the target strength, such measures as adding ground-granulated blast furnace slag to it need to be taken.

Calcium silicate hydrate, C-S-H, which is formed by the reaction between portlandite in the steelmaking slag and amorphous silica in the dredged soil, is an important factor in improving the strength of dredged soil mixed with steelmaking slag (Toda et al., 2018). In addition, such a mixture is difficult to solidify if it contains humic substances (Kaneko et al., 2016).

The effects of the consolidation of cement-treated soil on the shear strength of the resulting mixture have
been studied since the 1980s (e.g., Kobayashi and Tatsuoka (1982)). In case of consolidation through the application of overburden pressure immediately after mixing cement, for the same duration of curing, the relationship between the overburden pressure during curing and unconfined compressive strength is linear, and shear strength increases with an increase in the overburden pressure during curing (Yamamoto et al., 2002).

In general, clayey soil mixed with steelmaking slag takes more time to solidify than cement-treated soil, and the shear strength of the former mixture increases more consistently than that of the latter. Therefore, the relationship between the shear strength of a mixture of clayey soil and steelmaking slag and overburden pressure may change as the duration of curing increases. However, this has not yet been examined in the literature.

### 3 OUTLINE OF EXPERIMENTAL PROCEDURE

The kaolin clay obtained from Indonesia ($\rho_k = 2.61$ g/cm$^3$, $w_k = 71.4\%$, $w_p = 44.1\%$) and Metakaolin ($\rho_m = 2.66$ g/cm$^3$, $w_k = 67.4\%$, $w_p = 47.8\%$) were used. Furthermore, converter steelmaking slag ($\rho_s = 3.40$ g/cm$^3$) without aging treatment was used. Metakaolin is a phase produced by the dehydration of the OH ions in kaolinite at 500–650 °C, and contains a significant amount of amorphous silica. The clayey soil used in this study was a mixture with a ratio by mass of kaolin clay to metakaolin of 9:1. Table 1 lists the chemical compositions of the clayey soil, and Figure 1 depicts the curves of the accumulated particle sizes. Note that the curve in clayey soil was measured using a laser diffraction/scattering particle size distribution analyzer, and the curves are expressed in terms of volume percentage. The unconfined compressive strength of this clayey soil mixed with steelmaking slag after 0.21 days of curing was approximately 3 kN/m$^2$, that is, the soil solidified after consolidation when overburden pressure was applied to it immediately after it was mixed with the steelmaking slag.

| Major element | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | TiO$_2$ | CaO | MgO |
|---------------|--------|-------------|-------------|--------|-----|-----|
| Clayey soil   | 47.0   | 38.3        | 0.936       | 0.369  | 0.023 | 0.045 |

The specimens were prepared as follows: The clay had a prescribed water content ratio, and the water content ratio was 1.65 $w_k$ for kaolin clay. Table 2 shows the compositions expressed in volume and weight percentages under the given mixing conditions. Artificial seawater was used as pore water. The mixture of clayey soil and steelmaking slag was placed in a plastic mold. The specimens had a diameter of 50 mm and a target height of 100 mm after consolidation. In case of specimens with overburden pressure during curing, the mold-type consolidation apparatus was used (Figure 2). It could drain the pore water from the top and bottom of the mixture. In the case of specimens in atmospheric pressure during curing, plastic molds containing the mixture were tightly sealed and cured at a constant room temperature of 20 °C for the prescribed duration. After curing, unconfined compression tests and consolidated-undrained triaxial compression tests (CU test) were conducted on the specimens.

The conditions for the unconfined compression test were as follows: The durations of curing were 0.21 days (5 hours), 3 days, and 7 days. The overburden pressures were 0 kN/m$^2$, i.e., atmospheric pressure, 25 kN/m$^2$ (only for 3 days of curing), 50 kN/m$^2$, 100 kN/m$^2$, and 200 kN/m$^2$. The duration of 0.21 days of curing was chosen because this is the shortest duration of curing defined by the 3t method for overburden pressures. The axial strain rate was 1%/min.

The conditions of the CU test were as follows: The specimens were cured for 0.21 days, 3 days, 7 days, and 28 days. The overburden pressures applied during curing were 0 kN/m$^2$ (except to specimens cured for 0.21 days of curing), 50 kN/m$^2$, 100 kN/m$^2$, and 200 kN/m$^2$. Note that the shear strength of specimens cured at atmospheric pressure for 0.21 days could not be measured because the mixture in this study contained a large amount of clayey soil, and needed to be preconsolidated to conduct the CU test. After being cured for the prescribed durations, the specimens were consolidated under isotropic consolidation pressure and subjected to undrained-triaxial compression tests. In case of the specimens consolidated by overburden pressure during curing, the
isotropic consolidation pressure was identical to the overburden pressure during curing. In case of specimens which were cured at atmospheric pressure, the isotropic pressure was 50 kN/m². Clayey soil was preconsolidated at 50 kN/m² and consolidated under isotropic pressure at 50 kN/m². The axial strain rate of the specimens during the CU tests was 0.05%/min. Table 3 shows the conditions, the dry densities before and after isotropic consolidation, and volumetric strain at consolidation.

Table 3. Conditions for the CU tests, dry densities before and after isotropic consolidation, and volumetric strain at consolidation.

| Overburden pressure during curing (kN/m²) | Isotropic consolidation pressure during CU test (kN/m²) | Curing duration (days) | Dry density after preparation (g/cm³) | Dry density before consolidation (g/cm³) | Volumetric strain at consolidation (%) |
|------------------------------------------|------------------------------------------------------|-----------------------|---------------------------------------|----------------------------------------|---------------------------------------|
| 0                                        | 50                                                   | 3                     | 1.484                                 | 1.516                                  | 2.06                                  |
|                                          |                                                      | 7                     | 1.448                                 | 1.459                                  | 0.72                                  |
|                                          |                                                      | 28                    | 1.447                                 | 1.455                                  | 0.51                                  |
| 50                                       | 50                                                   | 0.21                  | 1.615                                 | 1.637                                  | 1.32                                  |
|                                          |                                                      | 3                     | 1.619                                 | 1.633                                  | 0.84                                  |
|                                          |                                                      | 7                     | 1.557                                 | 1.562                                  | 0.36                                  |
|                                          |                                                      | 28                    | 1.575                                 | 1.580                                  | 0.32                                  |
| 100                                      | 100                                                  | 0.21                  | 1.652                                 | 1.705                                  | 3.15                                  |
|                                          |                                                      | 3                     | 1.659                                 | 1.688                                  | 1.69                                  |
|                                          |                                                      | 7                     | 1.639                                 | 1.646                                  | 0.43                                  |
|                                          |                                                      | 28                    | 1.659                                 | 1.666                                  | 0.41                                  |
| 200                                      | 200                                                  | 0.21                  | 1.678                                 | 1.759                                  | 4.60                                  |
|                                          |                                                      | 3                     | 1.682                                 | 1.736                                  | 3.09                                  |
|                                          |                                                      | 7                     | 1.680                                 | 1.697                                  | 1.00                                  |
|                                          |                                                      | 28                    | 1.707                                 | 1.710                                  | 0.18                                  |

4 RESULTS AND DISCUSSION

4.1 Unconfined compression test

Figure 3 shows the relationship between unconfined compressive strength \( q_u \) and overburden pressure. For the same duration of curing, \( q_u \) increased with the overburden pressure during curing. The relationship between the unconfined compressive strength and the loading pressure during each of the durations of curing was almost linear.

Therefore, the relationship between \( q_u \) and overburden pressure for each of the durations of curing can be expressed as follows:

\[
q_u = \alpha \times \sigma_v + \beta
\]

where \( \alpha \) is \( \Delta q_u / \Delta \sigma_v \), and \( \sigma_v \) is the effective stress (\( \sigma / p \)). \( \beta \) is the value of \( q_u \) of the specimen cured at atmospheric pressure. Two factors might have increased the strength of the mixture cured under overburden pressure. One is the increase in its physical strength, that is, the shear strength improved through the chemical reaction. In case of 0.21 days of curing, the increase in chemical strength was small because the duration of curing was too short for the mixture to be solidified. Therefore, \( q_u \) in case of 0.21 days of curing was regarded as reflective of an increase in physical strength. Moreover, as shown in Figure 4, the change in \( e \) after consolidation was small. Therefore, the increase in strength from 0.21 days to 7 days of curing can be regarded as one in chemical strength. In addition, the change in \( \alpha \) over time indicated the increase in chemical strength with overburden pressure. Table 3 shows the coefficients \( \alpha \) and \( \beta \) of the approximate straight line of Equation (1) in Figure 4. The values of both \( \alpha \) and \( \beta \) increased with the duration of curing. The increase in \( \alpha \) shows that solidifying the mixture while consolidating it helped increase its chemical strength.

![Figure 3](image.png)

![Figure 4](image.png)

4.2 Consolidated-undrained triaxial compression test

Figure 5 shows the relationship between deviator stress \( q \) and axial strain \( \varepsilon_a \). Note that (i) shows the results for mixed soil and clayey soil cured for 0.21 days. From 0.21 days to 28 days of curing, the maximum deviator stress \( q_{\text{max}} \) increased with the overburden pressure, and the isotropic consolidation pressure increased during the curing.
shearing process. Table 3 shows that in case of 3 days of curing, the volume strains were 0.84%, 1.69%, and 3.09% at overburden pressures of 50 kN/m², 100 kN/m², and 200 kN/m², respectively, indicating a large change in volume. The specimen cured for 3 days was solidified, but the solidification was broken during the isotropic consolidation of the CU test, and $q$ decreased.

From the relationship between $q$ and $\varepsilon_a$, 3 days (ii) to 28 days (iv) of curing, in 3 days of curing in (ii) and 7 days of curing in (iii), the $q$ increases sharply as the axial strain increases up to 2% axial strain, and the $q$ increases when the axial strain exceeds 2%. On the 28 days of curing in (iv), the $q$ increased until the axial strain was 2%, and thereafter the $q$ became substantially constant.

![Graph](image1)

(i) 0.21 days of curing and clayey soil  
(ii) 3 days of curing  
(iii) 7 days of curing  
(iv) 28 days of curing  
Fig.5. Relationship between $q$ and $\varepsilon_a$ (CU test).

Figure 6 shows stress paths. Note that (i) shows the result of the mixed soil for 0.21 days of curing and that of the clayey soil. Regarding the test results of the mixed soil, the points on the $p'\text{-}q$ plane at the axial strains of 0.5%, 1%, 2%, and 4% are indicated by white points. The shapes of the stress paths at 0.21 days of curing and 3 days of curing were almost the same, but the maximum deviator stress at 3 days of curing was higher than that at 0.21 days of curing. When a line passing through a point on the stress path at the end of shearing and at the origin is defined as a failure criterion $M$, in all cases of (iii) curing for 7 days and (iv) 28 days, $M_{\text{peak}}$ was larger than $M$ at the time that this failure criterion was satisfied. This behavior is identical to that of cement-treated clay (Watabe et al., 2001). In addition, the path of stress tended to reach $M_{\text{peak}}$ at an axial strain lower than the maximum axial stress of 2% or less. It approached the failure criterion with increasing axial stress and then tended to remain constant at the failure criterion. At this time, in cases of (i) 0.21 days, (ii) 3 days, and (iii) 7 days of curing, $p'$ and $q$ increased and reached the failure criterion. On the contrary, in case of (iv) 28 days of curing, the stress path was above $M_{\text{peak}} = 3$ between 0.5% and 1% of axial strain; $q$ increased slightly, reached $q_{\text{max}}$ at 2% of axial strain, and stayed constant at the failure criterion at 4% of axial strain. These observations show that as the duration of curing increased, hardening progressed, and the path of stress advanced above $M_{\text{peak}} = 3$ from the point where the axial strain was low. In addition, the ratio of $q$ at a point deviating from the $M_{\text{peak}}$ line to $q_{\text{max}}$ increased with the duration of curing, and solidification advanced. Further, as the duration of curing increased, the ratio of axial strain to $q_{\text{max}}$ at which the former increased before deviating from $M_{\text{peak}}$ increased. However, in all cases, $q_{\text{max}}$ was not observed at $M_{\text{peak}}$.

![Graph](image2)

(i) 0.21 days of curing of clayey soil  
(ii) 3 days of curing  
(iii) 7 days of curing  
(iv) 28 days of curing  
Fig. 6. Relationship between $p'$ and $q$ for different curing durations (CU test).

Figure 7 shows the relationship between $p'$ and $q$ at $\sigma'_{\text{v}}=200$ kN/m² to help understand the change in the path of stress due to the differences in the durations of curing. A failure criterion passing through a point along the stress path at the end of shearing and at the origin is shown in the figure. As the duration of curing increased, the stress path passed through $q/p'=3$. At the end of the test, the shear resistance of the mixture is considered to be mainly exerted by friction. The slope of the failure criterion $q/p'$ increased as the duration of curing increased. After 0.21, 3 days, and 7 days of curing, as
shown in Figures 6(i), (ii), and (iii), \( q \) tended to increase even at the end of the experiment. The complete residual stress could not be measured at an axial strain of 17% to 18% at the end of the test. We thus predict that the fracture \( q/p' \) would have been further reduced. This tendency was observed in all cases where overburden pressure was applied. This shows that the internal frictional angle of mixed soil increased due to curing.

data for (iv) 28 days of curing when the overburden pressures were 0 kN/m² and 50 kN/m² shows that the isotropic consolidation pressure during the triaxial test was 50 kN/m² before and after isotropic consolidation. The volumetric strains at isotropic consolidation were as small as 0.51% and 0.70%, respectively. \( q_{\text{max}} \) at 50 kN/m² of overburden pressure during curing was 2.68 times \( q_{\text{max}} \) at 0 kN/m². Applying overburden pressure during curing at 50 kN/m² increased \( q_{\text{max}} \) in case of 28 days of curing by 2.68 times compared with that when the overburden pressure was 0 kN/m², i.e., atmospheric pressure.

Figure 9 shows the relationship between \( q/p' \) and axial strain. Note that (i) shows the result of mixed soil and clayey soil cured for 0.21 days. The maximum stress ratio of clayey soil was 1.5. For clayey soil mixed with steelmaking slag, the longer the duration of curing was, the clearer the peak of the stress ratio became. This means that \( M_{\text{peak}} \) occurred. In case of 3 days of curing (ii), gentle peaks were observed at overburden pressures of 50 kN/m² and 100 kN/m², and (iii) after 7 days of curing, clear peaks were observed under all conditions. In case of curing at an overburden pressure of 200 kN/m² for 3 days, the peak was not observed because solidification during curing was insufficient, and might have broken during isotropic consolidation in the CU test. In cases where the overburden pressure was applied during curing, the stress ratio at the peak was generally larger when the overburden pressure was lower. In cases of 7 days (iii) and 28 days of curing (iv), when comparing specimens cured under atmospheric pressure.
and with overburden pressure, the latter peaked with a low axial strain. The stress ratio then suddenly decreased and became constant. Thus, as the duration of curing increased, the value of $q_{\text{max}}$ of the mixed soil increased, and the peak of the stress ratio became clear. Thus, the presence of the peak of the stress ratio is a criterion for the solidification of the mixture.

The above shows that applying an overburden pressure of 50 kN/m$^2$ during 28 days of curing increased $q_{\text{max}}$ by 2.68 times compared with that at an overburden pressure of 0 kN/m$^2$, i.e., atmospheric pressure. Consolidation during curing enabled it to proceed easily. As the duration of curing increased and solidification advanced, the stress path moved above $M_{\text{peak}} = 3$ in the $p' - q$ plane and then transitioned to the failure criterion. In case of a constant overburden pressure, the longer the duration of curing was, the larger the internal frictional angle was at an axial strain of 17% to 18%. When the $p' - q$ plane was normalized by $\sigma'_c$, the larger the overburden pressure was during curing, the smaller the value of $q_{\text{max}}$ was for the mixture. This means that $q/\sigma'_c$, the change in $q$ when the overburden pressure was applied during curing, was smaller than one.

5 CONCLUSIONS

A unconfined compression test and a CU test were performed on specimens, consisting of clayey soil mixed with steelmaking slag, that were cured while applying overburden pressure.

The results of the unconfined compression test showed that the relationship between overburden pressure and $q_u$ during curing, for the same duration of curing, was linear, and both the slope and the intercept of the primary equation increased with the duration of curing.

The CU test showed that the application of an overburden pressure of 50 kN/m$^2$ during curing increased $q_{\text{max}}$ by 2.7 times when the mixture was cured under atmospheric pressure for 28 days. In addition, regardless of the presence of overburden pressure during curing, a peak appeared in the $p' - q$ plane as curing progressed, and, as solidification progressed, it increased beyond $q/p' = 3$. The internal frictional angle of the mixed soil at an axial strain of 17% to 18% increased when the overburden pressure was constant.

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