Accelerated curing and strength of soil–cement mixtures

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ABSTRACT

In situ soil–cement mixing is frequently used to minimize soil liquefaction, enhance soil strength and reduce soil permeability. For quality assurance purposes, drill core samples are taken from the soil–cement mixtures and unconfined compressive strength tests are carried out 28 days after mixing and placement, which may delay construction works. Clearly, there is a need to accurately predict the strength of soil–cement mixtures early. In this study, we prepared soil–cement mixtures with different proportions of clay, silt, sand, cement and water. The as-prepared specimens were subsequently cured at standard and various temperature, pressure and time conditions. We then compared the strength characteristics of the as-prepared soil–cement specimens. Unconfined compressive strength increases between 24 h and 48 h of accelerated curing; however, increasing the curing temperature does not lead to increases in strength. Compressive strength slightly increases with the curing pressure. Finally, the compressive strength depends on the cement and fines content and $W_{\text{Total}}/C$ of the soil–cement mixtures.

Keywords: soil–cement, unconfined compressive strength, accelerated curing

1 INTRODUCTION

Soil–cement mixing is widely used to improve the soil in underground works, mitigate liquefaction, increase soil strength and reduce soil permeability. The in situ mixing of soil and cement can be applied to various depths and increases the soil strength. Soil–cement mixtures improve the bearing capacity of foundation soils and enhance the stability of embankments and bulkhead walls.

For quality assurance purposes, 28 days after mixing the soil with cement, drill core samples are taken for unconfined compressive strength testing. Thus, it is very difficult to verify the in situ strength of the soil–cement mixture immediately after mixing, which may delay construction. Clearly, there is need to accurately predict the strength of soil–cement mixtures earlier than 28 days.

Laboratory tests using 3- and 28-day soil–cement specimens suggest that soil moisture, fines and cement content and the water to cement ratio affect the unconfined compressive strength. Nevertheless, there are few reports on soil–cement strength within the first few days of curing. Yamada and Fukuda (1995 and 1996) conducted laboratory tests and predicted soil–cement strength using soil–cement specimens that underwent high-temperature accelerated curing. To date, no curing method, suitable for practical use at construction sites where curing chambers are not always available, has been proposed.

In this study, we conducted laboratory tests to predict the 28-day compressive strength from soil–cement specimens that underwent accelerated curing in a construction site. The parameters considered for accelerated curing were temperature, pressure and time. Specimens were prepared by mixing cement slurry with soil samples. Then, the specimens were cured at $20 \pm 3 ^\circ C$ for 28 days or were cured at different temperature, pressure and time conditions. Subsequently, the strength characteristics of the specimens were compared and the factors affecting strength were evaluated.

2 MATERIALS

Soil–cement mixtures were prepared by mixing soil cement used in ground stabilization. The particle density and Atterberg limits for the clay, silt and sand making up the soil are presented in Table 1, and the grain-size distribution of each soil material is shown in Fig. 1.
Table 1. Physical properties of soil materials.

|                      | Clay | Silt | Sand |
|----------------------|------|------|------|
| Soil particle density $\rho_s$ (g/cm$^3$) | 2.71 | 2.43 | 2.67 |
| Liquid limit $w_l$ | 33.2 | 51.3 |  |
| Plastic limit $w_p$ | 11.9 | 35.9 |  |
| Plasticity index $I_p$ | 21.3 | 15.4 |  |

Soil samples with fines content (Fc) of 45% and 90% were prepared. Clay, silt and sand were mixed in the following proportions: 38:52:10 (Fc = 90%) and 18:27:55 (Fc = 45%). Soil moisture ($w$) of 80% and 40% was also used for soil samples with Fc = 90% and Fc = 45%, respectively.

A water-cement ratio (W/C) of 80% and 100% was selected for Fc = 90% and Fc = 45% mixtures, respectively. Four mixtures were made with the proportions given in Table 2. The $W_{\text{Total}}$ is the sum of the amount of water in the soil sample and the amount of water in the cement slurry. The $W_{\text{Total}}/C$ in Table 2 is the total amount of water to cement ratio for each soil–cement mixture.

Table 2. Soil–cement mixtures.

| Soil–cement sample | Fc (%) | Clay (kg/m$^3$) | Silt (kg/m$^3$) | Sand (kg/m$^3$) | w (%) | C (kg/m$^3$) | W (kg/m$^3$) | W/C (%) | $W_{\text{Total}}/C$ (%) |
|--------------------|--------|----------------|----------------|----------------|-------|-------------|-------------|---------|------------------------|
| A                  | 90     | 288           | 394            | 76             | 80    | 100         | 80          | 80      | 80                     | 686 |
| B                  | 90     | 123           | 168            | 32             | 80    | 550         | 440         | 80      | 127                    |     |
| C                  | 90     | 217           | 297            | 56             | 80    | 250         | 250         | 100     | 283                    |     |
| D                  | 45     | 156           | 234            | 477            | 40    | 250         | 250         | 100     | 239                    |     |

Fig. 1. Grain-size distribution of soil samples.

3 METHODS

3.1 Mixture and specimen preparation

Water was added to pre-mixed dry soils using a cement mixer. To ensure homogeneous distribution, we used a rubber spatula and the mixture was occasionally stirred by scraping the side and bottom of the mixing bowl during mixing. The duration of the mixing was 20 min. Subsequently, the wet soil sample was left for 1 h to remove the entrapped air and to allow for better water absorption.

Prior to mixing the cement slurry with the soil samples, the cement slurry was prepared by thoroughly mixing cement and water according to the proportions in Table 2. The mixing of soil and cement slurry lasted 10 min. Subsequently, the soil–cement mixture was placed into a cylindrical mould with a diameter of 5 cm and height of 10 cm. The height of the mould was increased by approximately 5 cm using packing tape around the top to minimize height loss owing to bleeding.

After a few hours, when the soil–cement specimens had hardened, the top surface of the specimens was trimmed and the specimen height was adjusted to 10 cm. Fig. 2 shows photos of the soil–cement specimens at the beginning and end of the preparation.

3.2 Curing procedures

All soil–cement specimens were cured under either accelerated curing or standard curing conditions in the moulds. For standard curing, the specimens were completely sealed in plastic sheets and fully immersed in water at 20 ± 3 °C for 28 days.

For accelerated curing, we considered the temperature, duration of curing, and pressure to optimize hardening in a short period. A commercial pressure cooker was used as the accelerated curing tank and two operating pressures were used.

Fig. 2. Preparation of soil–cement specimens.
In case 1, specimens were placed in the pressure cooker under atmospheric pressure and room temperature. In general, the internal pressure is approximately 0.1 MPa (gauge pressure) when the water boils in the pressure cooker, and the pressure regulator or safety valve is activated at >98 kPa. Therefore, because the internal pressure increases with boiling of water, a maximum pressure of 0.1 MPa was applied in the pressure cooker during curing.

In case 2, a similar pressure cooker was used but with two extra valves, a Presta valve and an air release valve at the top of the cooker. The Presta valve was used to apply the internal pressure of 0.1 MPa that was maintained during curing. Fig. 3 shows photographs of the pressure cookers used.

After placing the soil–cement specimens in the pressure cookers, we added water but did not cover the specimens. After securing the lid, the cooker was stored in an oven and the specimens were cured according to the conditions in Table 3. Fig. 4 shows photographs of standard and accelerated curing.

3.3 Testing program
The accelerated curing parameters are given in Table 3. After the completion of the standard and accelerated curing, unconfined compressive tests were performed following the JIS A 1216 standard test method and compared with the test results.

4 TEST RESULTS
The unconfined compressive strength $q_u$ for each test set is summarized in Table 4. The mean, maximum and minimum values are listed in Table 4. Figs. 5–9 show the strength results for accelerated and standard curing.

Fig. 5 shows the $q_u$ (mean value) for $F_c = 90\%$ as a function of curing time. The compressive strength $q_u$ of soil–cement specimen A-100°C and the corresponding $q_u-28\text{day}$ are nearly the same, whereas $q_u$ of soil–cement specimen B-100°C and C-100°C, is less than the corresponding $q_u-28\text{day}$. For A-100°C, B-100°C and C-100°C, the accelerated curing $q_u$ increases with increasing cement content and decreasing $W_{\text{Total}}/C$ regardless of curing time. For C-100°C, the strength appears to increase up to 48 h and then to decrease at 72 h. For curing at 100°C, there seems to exist an optimum curing time for maximum strength.

Fig. 6 shows the relation between $q_u$ (mean value) for $F_c = 45\%$ and curing time. In this figure, $q_u$ is compared with $q_u-28\text{day}$ for soil–cement specimen D.
cured at 80 °C and 90 °C, denoted as D-80°C, and D-90°C, respectively. The maximum strength is observed at 24 h in both cases, with no increase in strength at 48 h and 72 h. However, significant increase in $q_u$ is not observed at any curing temperature considered.

![Fig. 6. Average unconfined compressive strength for soil–cement specimen D.](image)

In Figs. 7–9, the strength ratio of accelerated curing $q_u$ is compared to the 28-day standard curing $q_u$.$\text{28day}$. In Fig. 7, the strength ratios for A-100 °C, B-100 °C and C-100 °C are shown as a function of curing time. The strength ratios for A-100 °C, B-100 °C and C-100 °C, D-80 °C and D-90 °C appear to maximize between 24 h and 48h, which constrains the optimum time for curing.

![Fig. 7. Unconfined compressive strength ratio for soil–cement specimens vs accelerated curing time.](image)

Fig. 8 shows the relation between the strength ratio for soil–cement specimen D and curing temperature. The strength ratio gradually decreases with increasing temperature. However, it is not clear if temperature has a strong effect as the cement and fines content and $W_{\text{Total}}$/C.

Next, Fig. 9 shows the relation between the strength ratio for soil–cement specimen D and curing pressure at 80 °C and 24 h. The strength ratio slightly increases with the curing pressure.

![Fig. 8. Unconfined compressive strength ratio for soil–cement specimen D vs accelerated curing temperature.](image)
5 CONCLUSIONS

We examined the effect of accelerated curing time, temperature and pressure on the strength of soil–cement mixtures. Based on the laboratory tests, we reach the following conclusions. First, unconfined compressive strengths and strength ratios increase between 24 h and 48 h. Second, increasing the curing temperature does not lead to increases in strength. Third, strength tends to slightly increase with the curing pressure. Finally, strength and strength ratio vary depending on the cement and fines contents and $W_{Total}/C$ of the soil–cement mixtures. The accelerated curing and strength data suggest that there is an optimum time window for achieving relatively high-strength soil–cement mixtures.

REFERENCES

1) Japan Cement Association (2014): Soil improvement manual for cement-based stabilizer, ISBN 978-4-88175-118-3, Gihodo Shuppan Co. Ltd. (in Japanese).
2) Japan Geotechnical Society (2009): Testing methods and their interpretation for geotechnical materials (in Japanese).