International Journal of GEOMATE, June, 2025 Vol.28, Issue 130, pp.78-86
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2025.130.4881
Geotechnique, Construction Materials and Environment

EXPERIMENTAL RESEARCH ON THE CURING TEMPERATURE OF LIQUEFIED STABILIZED SOIL

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*Corresponding Author, Received: 14 Jan. 2025, Revised: 21 March 2025, Accepted: 31 March 2025

ABSTRACT: Liquefied stabilized soil is an earthwork material in which muddy water (or clear water) and solidification material are kneaded into construction soil or construction sludge in an appropriate composition and then poured into the casting place while maintaining fluidity. It is widely used in urban areas to fill narrow spaces, such as structural backfilling, where compaction is difficult. This study investigated the relationship between curing temperature and unconfined compressive strength of liquefied stabilized soil based on the maturity concept. Laboratory tests were conducted at temperatures of 20°C, 40°C, and 60°C with varying wet densities and different types of solidification materials (Normal Portland Cement, High Early Strength Portland Cement, and Portland Blast Furnace Slag Cement). The results demonstrated that higher curing temperatures significantly reduced the required curing time, with specimens at 60°C achieving target strengths (target unconfined compressive strength at 28 days under 20°C curing: 78.5-258 N/mm2) in approximately one-fourth the time compared to 20°C curing. The maturity equation, originally developed for cement-improved soil, was found to be applicable for predicting strength development in liquefied stabilized soil, particularly in the temperature range of 40-60°C, regardless of the type of solidification material used.

Keywords: Liquefied stabilized soil, Unconfined compressive strength, Maturity, Strength prediction

1. INTRODUCTION

The technology for using liquefied stabilized soil was developed as part of the comprehensive project “Development of Recycling Technology and Restriction of Generation of Construction Byproducts” launched in 1993 by the former Japanese Ministry of Construction. In the early stages of developing liquefied stabilized soil technology, the research focused on manufacturing and construction techniques using excavated soil from construction sites as raw material, with the purpose of soil recycling [1]. Liquefied stabilized soil is often used for backfilling narrow spaces where rolling compaction is difficult, especially in urban areas. Liquefied stabilized soil is produced by kneading construction waste soil, construction sludge (containing muddy water or clear water), and solidification material at an appropriate ratio. It is poured into the placement site while maintaining fluidity and then it is backfilled. Appropriately blended liquefied stabilized soil has few cracks and is known to have a consistent quality even when containing different raw materials. Liquefied stabilized soil is mainly used for underground structures, backfilling of underground pipes, traces of mineral mining, aging pipes, structure blockages, and similar applications. As an example, there is a case study where liquefied stabilized soil was used for backfilling agricultural pipelines [2]. In this case, high-water-content cohesive soil excavated on-site was used as a raw material for liquefied stabilized soil to backfill narrow spaces. This application successfully achieved both soil recycling and quality backfilling of confined spaces with liquefied stabilized soil. In recent years, the application of liquefied stabilized soil to railway embankments has been under consideration [3]. Furthermore, studies have shown that using liquefied stabilized soil as backfill material can slightly reduce the horizontal displacement and story drift angle of buildings during earthquakes [4]. Liquefied stabilized soil technology enables soil recycling and backfilling/filling of narrow spaces at the same time.

Liquefied stabilized soil is an important process for determining the composition of the soil because it mainly uses construction-generated soil. The performance of liquefied stabilized soil varies depending on its use; however, it is mainly evaluated based on the wet density, flow value, bleeding rate, and unconfined compressive strength [5]. The wet density, flow value, and bleeding rate are measured while the material is still unsolidified. At the same time, specimens are prepared for unconfined compressive tests. The specimens are wet cured at 20°C, and an unconfined compressive strength test is performed after 28 days. Therefore, the compounding test requires a period of one month. It is possible to estimate the 28-day strength of liquefied stabilized soil based on its 7-day strength [6]. However, depending on the raw material soil, the estimation formula may not be correct, causing accuracy problems. In addition, if there is a significant change or modification in the raw material soil during construction, a new compounding test must be performed. If this is done during construction, the process could be delayed. Therefore, to shorten the compounding test, we focused on the cumulative temperature. Very few papers have discussed liquefied stabilized soil in relation to maturity (cumulative temperature). Therefore, we referred to the maturity equation for cement-improved soil (Eq. 1) devised by Nakama et al., which was based on previous research results by Rastrup (1954) and Metcalf (1963) [7-10]. Yamanobe et al. (2022) studied the estimation of the strength of cement-stabilized soil by high-temperature accelerated curing [11].

$$M = 2.1^{\{(t+10)/10\}} \times Tc \quad (1)$$

Where M is the cumulative temperature (degree days, ℃), t is the curing temperature (℃), and Tc is the curing time (days).

In the present study, we conducted experiments on the curing temperature and the unconfined compressive strength of liquefied stabilized soil and verified the correlation. In addition, we examined if Eq. (1) could be applied to liquefied stabilized soil since it generally has a smaller amount of solidification material and less strength than cement-improved soil.

2. RESEARCH SIGNIFICANCE

This study investigated the correlation between the curing temperature and unconfined compressive strength in liquefied stabilized soil, which typically requires a curing period of 28 days for mixture design tests. Based on the maturity concept, our experiments revealed that despite the small amount of solidification material and low strength, certain mixtures showed a correlation between the cumulative temperature and the strength. This finding suggests the possibility of predicting the 28-day strength from early-age results, potentially reducing the testing time. Further research with various sources of soil and cement could lead to practical implementation.

3. MATERIALS AND COMPOUNDING PLAN FOR LIQUEFIED STABILIZED SOIL

In consideration of the reproducibility of the compounding test, we used commercially available Kibushi clay for the raw material soil due to its stable and consistent supply availability. In addition, silica sand was used to adjust the wet density of the liquefied stabilized soil. Normal Portland cement (N), high early strength Portland cement (H) and Portland blast -furnace slag cement type B (BB) were used as solidifying materials (Table 1). An example of quality control status for liquefied stabilized soil is shown (Fig. 1).

Here, “muddy water” refers to a mixture of Kibushi clay and water, and “adjusted muddy water” refers to muddy water with silica sand added to adjust the density. Liquefied stabilized soil is made by adding a solidifying agent to muddy water or adjusted muddy water. The wet density of the liquefied stabilized soil is abbreviated as “wet density” hereafter. The compounding of the liquefied stabilized soil was based on three types: 1.25 g/cm^3 for the muddy water density and 1.4, 1.5, and 1.6 g/cm^3 for the adjusted muddy water density (Table 2). After preparing the liquefied stabilized soil, a quality test was conducted. Fig. 2 shows the compounding test flow.

Table 1 Physical properties of materials

Kibushi clay	Soil particle density (g/cm^3)		2.445
	Grain size distribution	Gravel (%)	0.000
		Sand (%)	5.700
		Silt (%)	42.00
		Clay (%)	52.30
	Maximum grain size (mm)		0.850
Silica sand	Soil particle density (g/cm^3)		2.590
	Grain size distribution	Gravel (%)	0.000
		Sand (%)	95.1
		Silt (%)	4.9
		Clay (%)	
	Maximum grain size (mm)		0.425
Normal Portland cement (N)	Specific gravity (g/cm^3)		3.150
High early strength Portland cement (H)	Specific gravity (g/cm^3)		3.130
Portland blast furnace slag cement type B(BB)	Specific gravity (g/cm^3)		3.040

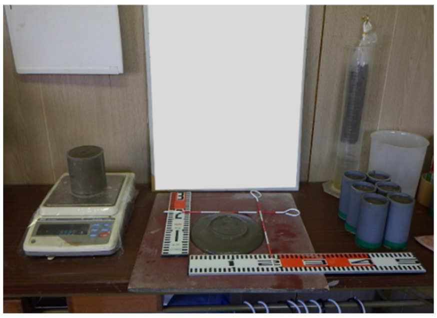

Fig. 1 Quality control status for liquefied stabilized soil

Addition of water to raw soil

↓

Production of muddy water

↓

Adjustment to a predetermined muddy density

↓

Addition of silica sand

↓

Addition of solidification material

↓

Adjustment to a predetermined muddy density with adjusted density

↓

Compounding test
a) Flow test
b) Bleeding test
c) Density test
d) Unconfined compressive strength test

Fig. 2 Compounding test flow

The four test methods are described below.

a) Flow test

The fluidity of the liquefied stabilized soil was evaluated based on the flow value using the cylinder method. A cylinder with a diameter of 8 cm and a height of 8 cm was filled with liquefied stabilized soil placed on a smooth board. The flow value is the diameter of the liquefied stabilized soil that expands when the cylinder is pulled up (Fig. 3). In the flow value measurement method, the maximum diameter of the liquefied stabilized soil spread on the board and the diameter in the direction perpendicular to it is averaged if the difference in the measured value is 20 mm or less. If there is a greater difference, the test is performed again.

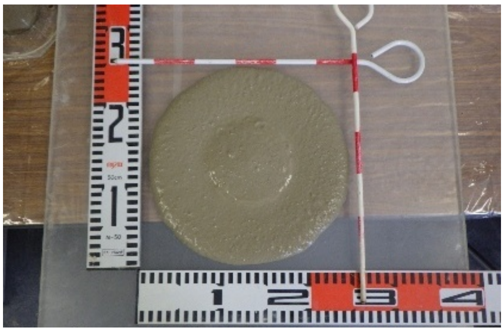

Fig. 3 Flow test of liquefied stabilized soil

b) Bleeding test

Immediately after mixing, the liquefied stabilized soil was poured into a polyethylene bag (diameter 5 cm, length about 50 cm) to prevent the entry of air. The initial volume of liquefied stabilized soil was measured in a graduated cylinder filled with water. This test specimen was left for 3 and 20 h, and the amount of separated water was measured. The bleeding rate was determined by the ratio of the separated amount of water to the initial volume. In this test, the values at 20 h from the start of measurement were adopted.

c) Unconfined compressive strength test

The specimen for the unconfined compression test was prepared using a small mold with a diameter of 5 cm and a height of 10 cm. Three samples were produced for each mixture. The curing method was performed by sealed curing at 20°C. An unconfined compression test was performed at 28 days of curing time, and the average value of the three samples of mixtures was obtained (Fig. 4).

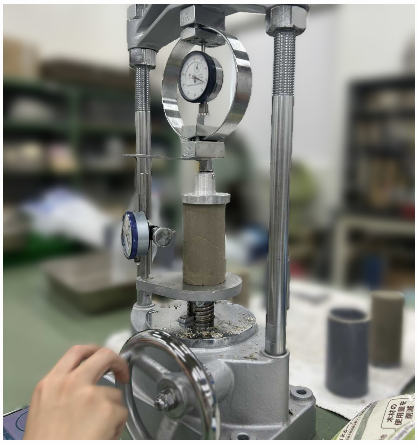

Fig. 4 Unconfined compressive strength testing of liquefied stabilized soil

d) Density test

A quantitative container was filled with the liquefied stabilized soil. The weight was measured and the value was divided by the volume to calculate the wet density.

Table 2 Compounding of liquefied stabilized soil

No	Muddy water with adjusted density	Wet density	Amount of solidification material		Kibushi clay	Water	Silica sand
	(t/m^3)	(t/m^3)	(kg/m^3)		(kg/m^3)	(kg/m^3)	(kg/m^3)
A	1.40	1.443	80	N	375.7	734.4	290.0
B	1.50	1.541	80	N	344.0	672.4	484.0
C	1.60	1.638	80	N	312.5	611.0	676.5
D	1.50	1.551	100	N	344.0	672.4	484.0
E	1.50	1.561	120	N	344.0	672.4	484.0
F	1.50	1.541	80	H	344.0	672.4	484.0
G	1.50	1.540	80	BB	344.0	672.4	484.0

Note: All compounds used 1.25 g/cm³ muddy water.

4. QUALITY TEST RESULTS OF LIQUEFIED STABILIZED SOIL

The quality test results of the liquefied stabilized soil are shown (Table 3). For "A," "B," and "C," the amount of solidification material was constant and the change in wet density was confirmed. In addition, the wet density of "B," "D," and "E" was constant, and the change in the amount of solidification material was confirmed. The wet density and the amount of solidification material were constant in compounding "B," "F," and "G," and it was confirmed that the changes were due to the difference in the solidification material.

The relationship between the curing time (days) and the unconfined compressive strength is shown (Fig. 5). This figure presents the relationship between curing time (days) on the horizontal axis and unconfined compressive strength on the vertical axis. The wet density tended to increase, and the unconfined compressive strength tended to increase as the amount of solidification material increased. The unconfined compressive strength of normal Portland cement ("B") and high early strength Portland cement ("F") was about 2.3 and 1.4 times that of "B" at a curing time of 3 and 7 days, respectively. At a curing time of 28 days, the amount of "F" was about 1.2 times that of "B". Portland blast -furnace slag cement type B ("G") was about 1.0 and 1.4 times that of "B" at a curing time of 3 and 7 days, respectively. At a curing time of 28 days, the amount of "G" was about 1.4 times that of "B".

The relationship between wet density, bleeding rate, and flow value is shown (Fig. 6). This figure presents wet density on the horizontal axis, flow value on the left vertical axis, and bleeding rate on the right vertical axis. The flow values and bleeding rates show a decreasing tendency as the wet density increases.

As the wet density of liquefied stabilized soil increases, the unconfined compressive strength increases and the bleeding rate decreases, indicating improved quality. However, careful consideration is required in mixture design as the flow value decreases, resulting in loss of flowability [12].

5. OVERVIEW OF TEMPERATURE CURING EXPERIMENT OF LIQUEFIED STABILIZED SOIL

A large constant-temperature water tank was used to produce the curing temperature of the liquefied stabilized soil (Fig. 7). The tank operated at temperatures ranging from 5°C to 95°C, with a temperature variation of ±2°C. The specimen for the unconfined compression test was cured in a well-sealed polyethylene bag. The curing temperatures were 20°C, 40°C, and 60°C. The selection of curing temperatures was based on the standard curing

Table 3 Quality test results of liquefied stabilized soil

No	Wet density (t/m^3)	Flow value (mm)	Bleeding rate (%)	Unconfined compressive strength (28 days) (kN/m^2)
A	1.472	490	0.93	78.5
B	1.548	395	0.90	79.5
C	1.632	350	0.43	149.0
D	1.554	297	0.36	156.4
E	1.568	331	0.24	258.0
F	1.548	353	0.45	92.5
G	1.542	440	0.77	112.0

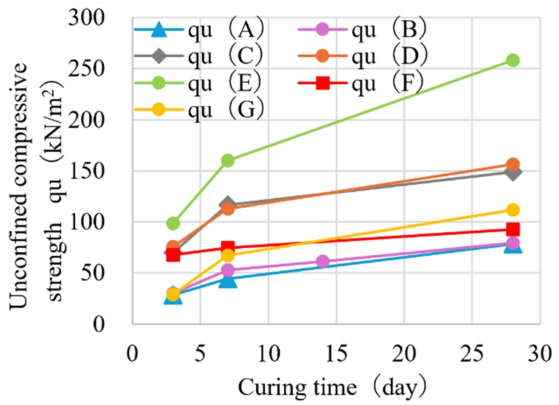

Fig. 5 Relationship between curing time and unconfined compressive strength

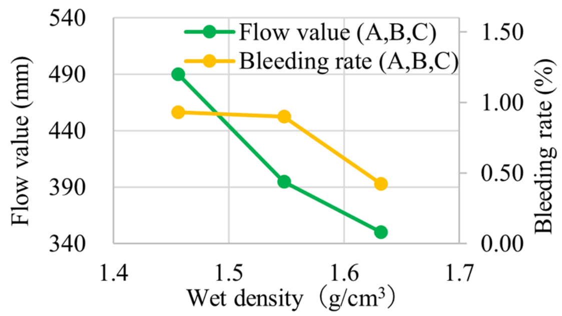

Fig. 6 Relationship between wet density, bleeding rate, and flow value

condition of 20°C for 28 days in a humid environment, which is the reference strength condition for liquefied stabilized soil. The temperatures of 40°C and 60°C were selected as double and triple the standard temperature, respectively, to systematically evaluate the acceleration effects of elevated temperatures on strength development. The unconfined compression test was performed at curing times of 3, 7, 14, and 28 days at 20°C, at curing times of 1, 3, and 7 days at

40°C, and at 1 day at 60°C. It was confirmed that the temperature of the test specimen was about the same as the water temperature within 1 h (Fig. 8). The figure presents the relationship between curing time (hours) on the horizontal axis and temperature (°C) on the vertical axis. Temperature measurements were performed using thermocouples connected to a four-channel data logger. Specimen temperature was monitored by installing a thermocouple at the center of the liquefied stabilized soil specimen, which was cast in a cylindrical mold (50 mm diameter × 100 mm height). Additional thermocouples were installed to record both ambient temperature and water temperature in the constant temperature water bath (Fig. 9). The same trend was observed at the temperature of the test specimen at a curing temperature of 60°C.

The specimens were cured in a large constant-temperature water tank, and temperature variations within the specimens were confirmed to be less than ±1°C. This ensured uniform curing conditions throughout the specimens, resulting in consistent development of strength.

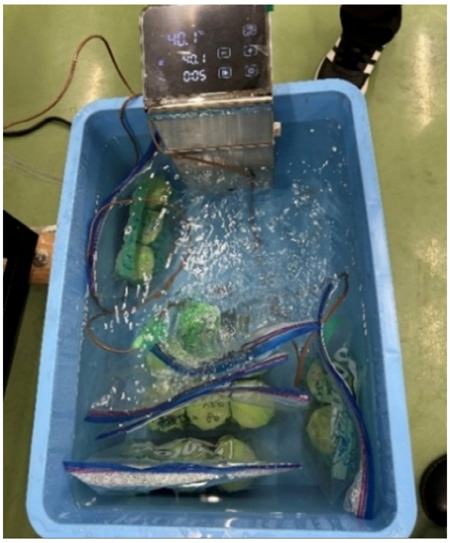

Fig. 7 A large constant-temperature water tank

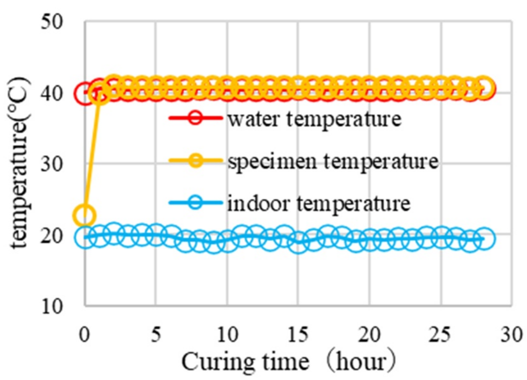

Fig. 8 Relationship between water temperature and specimen temperature

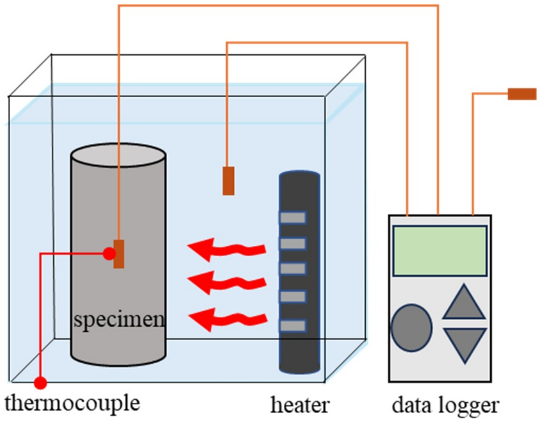

Fig. 9 Temperature measurement status

6. RESULTS OF TEMPERATURE CURING EXPERIMENT OF LIQUEFIED STABILIZED SOIL

The results of the curing temperature experiment of the liquefied stabilized soil are shown (Table 4). Next, the compressive strength ratio at each curing time was calculated when the unconfined compressive strength at a curing time of 28 days was set to 1 at a curing temperature of 20°C for each compounding (Table 5). In addition, the ratio of the cumulative temperature at each curing time when the cumulative temperature at 28 days was set to 1 was calculated from Eq. (1) (Table 6).

The relationship between the compressive strength ratio due to the difference in the wet density of the liquefied stabilized soil is shown (Fig. 10).

At 20°C, the compressive strength ratio was similar to that of all three compounding. In addition, when compared with the cumulative temperature ratio, a difference of about two-fold was confirmed. At 40°C, the correlation was confirmed at 1 and 3 days compared with the cumulative temperature ratio. The compressive strength ratio was 0.25–0.28 at a curing time of 1 day. At a curing time of 3 days, it was 0.55–0.82. For “B”, the temperature ratio was almost the same as the cumulative temperature ratio for a curing time of 7 days. At 60°C, the compressive strength ratio was 0.63–0.78, and “A,” “B,” and “D” were almost the same. Compared with the compressive strength ratio and the cumulative temperature ratio, it was about the same level.

The relationship between the compressive strength ratio due to the difference in the amount of solidification material is shown (Fig. 11). At 20°C and 40°C, the trend was almost the same as “A”, “B”, and “C”. The compressive strength ratio was 0.25–0.31 at a curing time of 1 day. At a curing time of 3 days, it was 0.60–0.82. There was a slight difference at a curing time of 7 days. At 60°C, the compressive strength ratio was 0.78–0.82, and “B,” “D,” and “E” were almost the same. Compared with the compressive strength ratio and the cumulative temperature ratio, it was about the same level.

The relationship between the compressive strength ratios of the different types of solidification material in the liquefied stabilized soil is shown (Fig. 12).

At 20°C, “F” was about twice that of “B” at a curing time of 3 days. The intensity was about 1.3 times higher at a curing time of 7 days. "B" and "F" showed the same trend. At 40°C, “B” was correlated with the cumulative temperature ratio, but the compressive strength ratio of “F” tended to be larger than the cumulative temperature ratio at a curing time of 1 and 3 days and it was smaller at a curing time of 7 days. The same trend was seen in "G". At 60°C, the compressive strength ratio was 1 for a curing time of 1 day, and the compressive strength ratio and cumulative temperature ratio were about the same level. The cumulative temperature ratio of "G" was about half of the compressive strength ratio.

Table 4 Curing temperature of liquefied stabilized soil and unconfined compressive strength at each curing time

No.	Curing temperature θ (°C)	Unconfined compressive strength qu (kN/m^2) Curing time (days) 1	3	7	14	28
A	20	—	28.5	44.5	—	78.5
	40	20.0	43.0	89.0	—	—
	60	49.5	—	—	—	—
B	20	—	30.0	53.0	61.5	79.5
	40	22.5	65.0	148.5	—	—
	60	61.0	—	—	—	—
C	20	—	70.0	116.5	—	149.0
	40	40.0	100.0	150.0	—	—
	60	104.5	—	—	—	—
D	20	—	76.0	113.0	—	156.4
	40	48.5	115.0	203.0	—	—
	60	128.0	—	—	—	—
E	20	—	98.5	160.0	—	258.0
	40	65.0	154.5	302.0	—	—
	60	195.0	—	—	—	—
F	20	—	68.0	74.5	—	92.5
	40	60.0	93.0	130.0	—	—
	60	92.0	—	—	—	—

The relationship between the curing period and unconfined compressive strength (Compounding B) is shown (Fig. 13). This graph demonstrates that the curing time could be shortened by adjusting the curing temperature. The strength at 28 days of curing at 20°C corresponds to the strength at approximately 4 days with curing at 40°C and approximately 1 day with curing at 60°C. This resulted in a reduction of the curing time by approximately 24 days at 40°C and approximately 27 days at 60°C. The results of the investigation on different types of solidification materials are shown. Similar trends to Compounding B were observed regardless of the type of solidification material (Fig. 14).

Table 5 Compressive strength ratio of liquefied stabilized soil

No.	Curing temperature θ (°C)	Compressive strength ratio ($qu_{day \cdot x°C}/qu_{28 \cdot 20°C}$) Curing time (days) 1	3	7	14	28
A	20	—	0.36	0.57	—	1
	40	0.25	0.55	1.13	—	—
	60	0.63	—	—	—	—
B	20	—	0.38	0.67	0.77	1
	40	0.28	0.82	1.87	—	—
	60	0.77	—	—	—	—
C	20	—	0.47	0.78	—	1
	40	0.27	0.67	1.01	—	—
	60	0.70	—	—	—	—
D	20	—	0.49	0.72	—	1
	40	0.31	0.74	1.30	—	—
	60	0.82	—	—	—	—
E	20	—	0.38	0.62	—	1
	40	0.25	0.60	1.17	—	—
	60	0.76	—	—	—	—
F	20	—	0.74	0.81	—	1
	40	0.65	1.01	1.41	—	—
	60	1.00	—	—	—	—

Table 6 Cumulative temperature and cumulative temperature ratio

	Curing temperature θ (°C)	Curing time (days) 1	3	7	14	28
Cumulative temperature (°C)	20	9.3	27.8	64.8	129.7	259.3
	40	40.8	122.5	285.9	—	—
	60	180.1	—	—	—	—
Cumulative temperature ratio	20	0.036	0.107	0.250	0.500	1
	40	0.158	0.473	1.103	—	—
	60	0.695	—	—	—	—

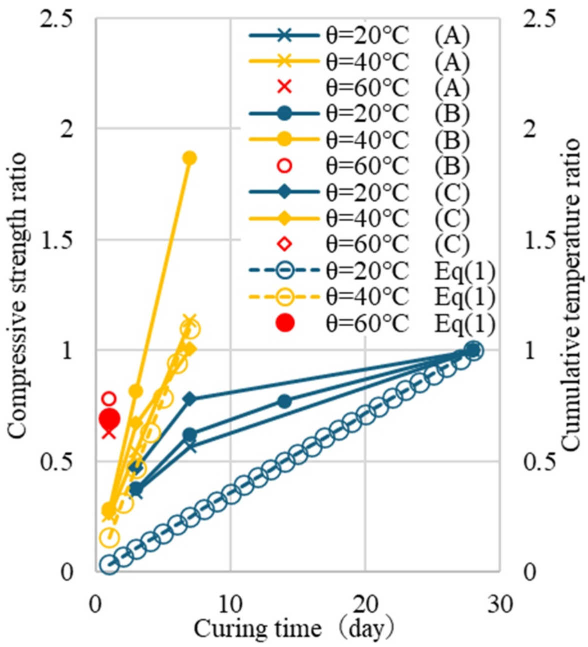

Fig. 10 Relationship between curing time and compressive strength ratio (A, B, C)

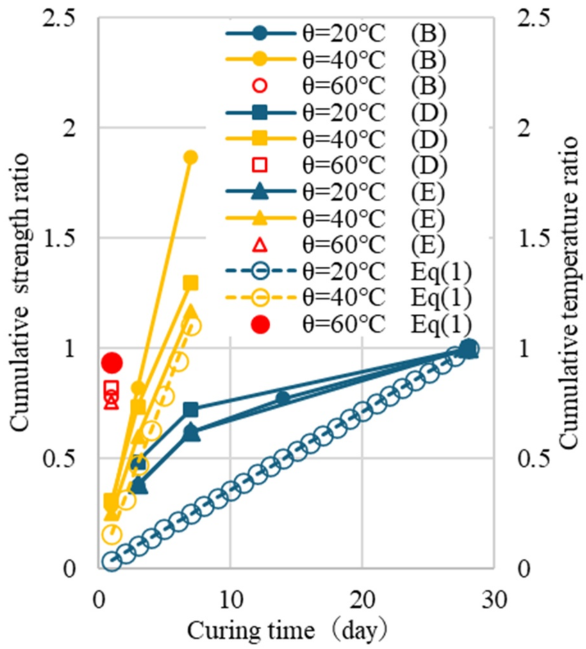

Fig. 11 Relationship between curing time and compressive strength ratio (B, D, E)

7. CONCLUSION

In this study, we examined the correlation between the curing temperature and the unconfined compressive strength in liquefied stabilized soil. The results of our experiments confirmed the differences in the wet density, the amount of solidification material, and the type of solidification material in the same raw material.

In addition, we confirmed the correlation with the cumulative temperature ratio using Eq. (1). The main findings are as follows:

a) In the compounding test with different wet densities, the compressive strength ratio was similar at θ = 20°C and θ = 60°C.

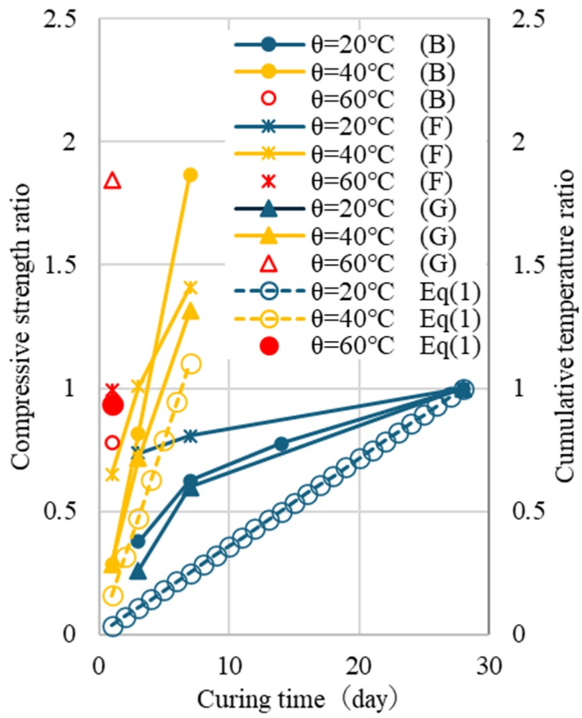

Fig. 12 Relationship between curing time and compressive strength ratio (B, F, G)

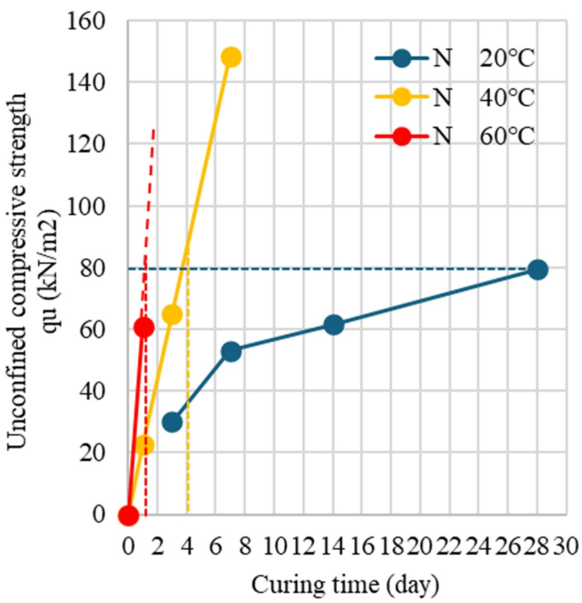

Fig. 13 Relationship between curing time and unconfined compressive strength (Compounding B)

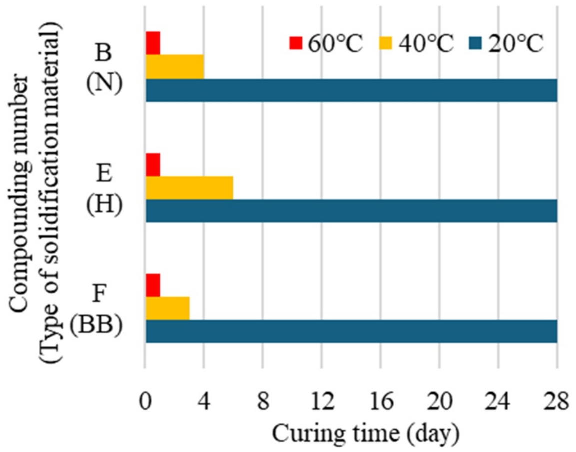

Fig. 14 Relationship between curing time and unconfined compressive strength

The compressive strength ratio was similar at the curing times of 1 and 3 days at θ = 40°C. The correlation between the cumulative temperature ratios was confirmed at the curing times of 1 and 3 days for θ = 40°C. θ = 60°C was about the same level as the cumulative temperature ratio. Eq. (1) was applicable in the range of θ = 40–60°C.

b) In the compounding test with different amounts of solidification material, the wet density and amount of solidification material did not have a significant effect on the curing temperature.

c) Eq. (1) was generally applicable even if the type of solidification material was changed.

d) The study demonstrated that higher curing temperatures enabled a significant reduction in curing time to achieve the specified unconfined compressive strength.

The liquefied stabilized soil exhibited a small amount of solidification material and low strength; however, a correlation between the cumulative temperature and the unconfined compressive strength was observed in the compounding of one part. The maturity equation Eq. (1) was originally developed for cement-improved soil, but our experimental results confirm its applicability to liquefied stabilized soil within the tested conditions (target unconfined compressive strength at 28 days under 20°C curing: 78.5-258 N/mm^2, curing temperature: 20-60°C). It should be noted that further validation studies may be necessary when extending these findings to conditions beyond the present scope, specifically concerning varying soil compositions and extreme temperature regimes. While this study focused on short-term strength development, we recognize that the long-term performance of liquefied stabilized soil under varying environmental conditions remains an important area for future research. Further investigation is needed to understand the effects of environmental factors, such as temperature variations and humidity, on long-term strength characteristics. In the future, we will conduct experiments on different types of raw soil and cement, incorporating advanced regression analysis, to accumulate additional data. Furthermore, we plan to conduct verification experiments under actual field conditions to examine in detail the effects of temperature variations and environmental factors. It is also important to analyze microstructural changes using SEM and XRD to understand the effects of curing temperature on microstructure development. To be able to handle various types of compounding, we intend to continue studying the relationship between the cumulative temperature and unconfined compressive strength of liquefied stabilized soil, and the application of Eq. (1).

The findings of this study are expected to contribute to reducing the time required for mixture design determination of liquefied stabilized soil by practicing engineers and improving quality control efficiency, leading to shorter construction periods and cost reduction. Since mixture design and quality control tests are conducted using specimens of 50 mm diameter × 100 mm height, the accelerated curing method is feasible using the temperature-controlled water bath employed in this study. Furthermore, the application of the maturity equation enables the prediction of strength development under various temperature conditions, allowing for more sophisticated quality control in field applications.

8. ACKNOWLEDGMENTS

We sincerely thank Mr. Eiki Sada, Mr. Yuri Sueda, and Mr. Yuma Tanaka, senior students in the Department of Urban Environmental Engineering, Faculty of Creative Engineering at the Chiba Institute of Technology, for their valuable contributions to the experimental work of this study.

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