Influence of Curing Temperature on Strength of Cement-treated Soil

Student: Hwanik Ju

Faculty Advisor: George M. Filz (filz@vt.edu)

Sponsors: Virginia Tech

Start/Completion Dates: August 2017 / August 2020

Project Background

The strength development of cement-treated soil is significantly influenced by characteristics of the in-situ soil, the amount of added cement and water, mixing conditions, and curing conditions. Curing temperature is an important factor that influences the strength of the cement-treated soil, at least in the short term. The temperature of deep-mixed elements increases due to cement hydration and then deceases as the heat dissipates. It is well-known that the strength of cement-treated inorganic soil increases with curing time and curing temperature. However, the influence of constant and changing curing temperatures on the short-term and long-term strength is not widely investigated. Moreover, due to lack of standard protocols for curing temperature in construction QC/QA programs, questions can arise during construction about the proper temperature for curing specimens prior to UCS testing.

Project Objectives

The principal objectives of this research and the corresponding benefits are listed below:

1. Investigate the influence of curing temperature on unconfined compressive strength (UCS) of cement-treated soil
2. Develop a UCS predictive equation that accounts for the influences of constant and changing curing temperatures on the short-term and long-term strength

Materials and Methods

The fabricated base soil for this study was lean clay (CL), and the water content (w) was 35%. The same binder (Portland cement) and the same mixture proportions that were selected for the previous research were used for this research. After mixing and molding, the specimens were cured in water baths maintained at 25, 35, 45, and 55 °C for 3, 7, 14, and 28 days to study the influence of constant curing temperature. For the study of the influence of changing curing temperature, all specimens were cured for 28 days according to the curing plans presented in Table 1. After curing, UCS tests were conducted to measure the strength of the specimens.

Table 1. Curing plans for the study of the influence of changing curing temperature

Specimen	Curing time (days)		Specimen	Curing time (days)	
	First period at 45 °C	Second period at 25 °C		First period at 25 °C	Second period at 45 °C
A	0	28	--	--	--
B1	7	21	B2	21	7
C1	14	14	C2	14	14
D1	21	7	D2	7	21
--	--	--	E	0	28

Findings

1. Influence of constant curing temperature on short-term strength

Based on the UCS test data (Figure 1), the influence of curing time is more significant at early curing times, while the curing temperature has more effect at later curing times. Additionally, the influence of curing temperature on UCS is more significant when the amount of cement is smaller. This indicates that the influence of curing temperature is related to the amount of cement. By adding a normalized curing temperature term to the w_t:c term in the strength from previous research, a revised strength equation that accounts for the influence of constant curing temperature was developed as presented below. The coefficients were determined through a least squares regression analysis (b_1 = 15.9, b_2 = 23.5, $b_{3,1}$ = -1.63, $b_{3,2}$ = 0.485, and b_4 = 2.12). The coefficient values for the equation vary depending on the base soil type. The equation provided a very good fit between predicted UCS and measured UCS (R^2 = 0.96). Therefore, the equation below can be used to predict UCS of cement-treated soil as a function of curing time, mixture proportion, and curing temperature for the curing times of 3 to 28 days, curing temperatures of 21 to 55 °C, and the range of mixture proportions selected in this research ($\alpha_{in\text{-}place}$ = 125 to 350 kg/m^3 and w:c = 0.6 to 1.4).

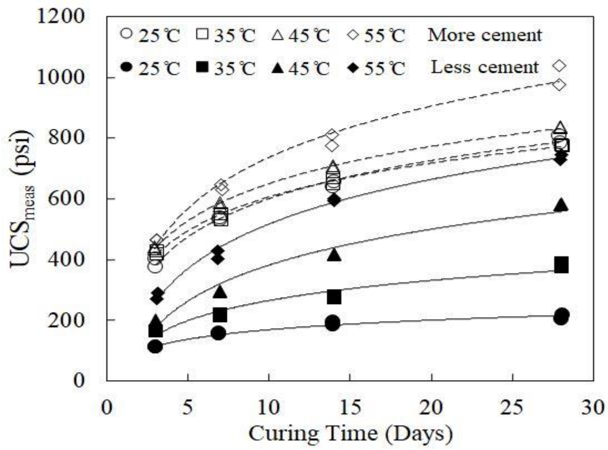

Figure 1. Relationship between UCS$_{meas}$ & curing time

$$\frac{UCS_{pred}}{p_a} = \left[b_1 + b_2\, ln\left(\frac{t}{1\ day}\right)\right] [w_t\!:c]^{b_{3,1}+b_{3,2}\frac{T-21\,°C}{21\,°C}} \left[\gamma_{d,mix}\!:\gamma_w\right]^{b_4}$$

where b_1, b_2, $b_{3,1}$, $b_{3,2}$, and b_4 are dimensionless coefficients, T is the curing temperature in °C, and T_0 is the reference temperature in °C (21 °C in this research).

2. Influence of changing curing temperature on short-term strength

As shown in Figure 2, UCS increases with longer curing time and higher curing temperature, and the effects of elevated curing temperature are greater at later curing times than at early curing times. In other words, the specimen cured at a low temperature then cured at a high temperature is stronger than the specimen cured at a high temperature first. Although there are some qualitative explanations based on the concepts of cement hydration reaction rates that support the test results, additional UCS data with different curing conditions and a deeper understanding of cement hydration reactions are necessary to develop a comprehensive predictive equation.

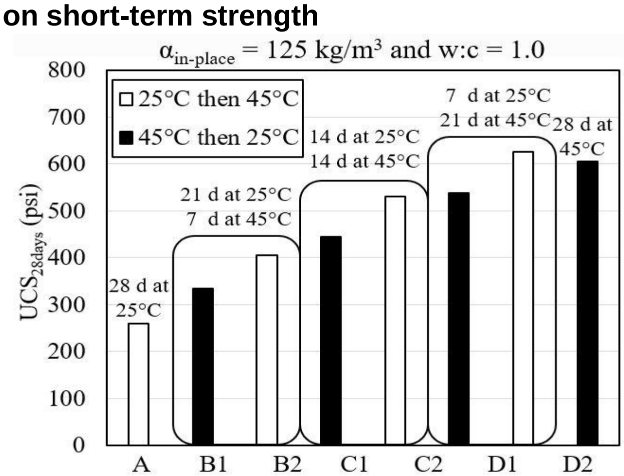

Figure 2. UCS$_{28days}$ corresponding to curing plan

Further Research Tasks

1. Review literature related to the chemistry and physics of cement hydration reactions
2. Perform additional UCS tests with changing curing temperature and long curing times
3. Develop a unified UCS predictive equation that accounts for the influence of constant and changing curing temperature over a wide range of curing times