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Research Paper

Prediction Formula For Unconfined Compressive Strength of Cement Treated Soft Soil During Full Age

J.J. Yang [1], H. Liu [2], Q. Liu [3], M.R. Dong [4], M. Wang [5] and R. Mi [6]

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ABSTRACT

Cement stabilization method is one of the ground improvement techniques and has been also used for the purpose of utilization of dredged clay or construction muck. The long-term strength of cement soil is influenced by many factors such as cement content, water content, curing age and soil properties. In this study, a new formula without fitting parameters, which was based on the functional relationship without fitting parameters between the unconfined compressive strength and the curing age which was proposed by Yang et al., was proposed for predicting the unconfined compressive strength of cement treated soil during full age, The results show that the formula can properly predict the strength growth of cement treated soil by comparing with the experimental data that was cited from the literatures.

1. Introduction

The unconfined compressive strength (UCS) is the key index in designing of the cement treated soil. If the functional relationship between the UCS and the age is known, according to the design strength, it is possible to reduce the numbers and the periods of the proportion tests, and it can also be used to predict the long-term strength of cement treated soil.

Numerous studies have proposed the formulas on the relationship between the UCS and the age of cement treated soil that with or without fitting parameters (Table 1).

It is necessary to determine the fitting parameters by using the experimental data in Eqs. (1)-(11). Among those formulas, the fitting parameters of Eqs. (1)-(5) are needed to be determined by fitting before the predicting of strength, and the fitting parameters of Eqs. (6)-(11) have already been determined by fitting with certain experimental data and therefore, it is impossible that Eqs. (6)-(11) are applicable to other soils.

Eq. (12) does not contain fitting parameters, the UCS at any age can be calculated from the UCS at some age

[1] Professor, Key Lab of Marine Environment and Ecology, Ministry of Education, Ocean University of China, College of Environmental Science and Engineering, Ocean University of China, Qingdao 266100, CHINA, jjyang@ouc.edu.cn
[2] Doctoral student, Key Lab of Marine Environment and Ecology, Ministry of Education, Ocean University of China, College of Environmental Science and Engineering, Ocean University of China, Qingdao 266100, CHINA, liuhaocom@163.com
[3] Associate Professor & Corresponding author, College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, CHINA, sunnyseasea@163.com
[4] Doctoral student, Key Lab of Marine Environment and Ecology, Ministry of Education, Ocean University of China, College of Environmental Science and Engineering, Ocean University of China, Qingdao 266100, CHINA, Dmr1989@163.com
[5] Master student, Key Lab of Marine Environment and Ecology, Ministry of Education, Ocean University of China, College of Environmental Science and Engineering, Ocean University of China, Qingdao 266100, CHINA, 694501276@qq.com
[6] Master student, Key Lab of Marine Environment and Ecology, Ministry of Education, Ocean University of China, College of Environmental Science and Engineering, Ocean University of China, Qingdao 266100, CHINA, 1019323190@qq.com
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and corresponding design parameters of cement treated soil, and the calculated results were almost consistent with experimental results within 180 days (Yang et al. 2019; Yang et al. 2017). However, the calculated strength increases infinitely with age, which is not in accordance with the law of strength growth of cement treated soil (Zhang et al. 2006), due to its exponential form.

Table 1. Formulas on the UCS and the age of cement treated soil

Classification	Authors	Formulas	No.	Note
with fitting parameters	Nagaraj and Miura (1996); Yamadera (1997)	$\frac{q_u}{q_u(14)} = a + b\ln(t)$	(1)	q_u is predicted UCS; t is curing age; $q_u(14)$ is UCS at 14 days; a, b are fitting parameters.
	Kitazume et al. (2003); Saitoh (1988)	$q_u = a + b\log(t)$	(2)	a and b are fitting parameters.
	Sakka et al. (2000)	$q_u = \frac{\alpha t}{3.46 + 0.87t} K_E[R - 0.28exp(-0.025w_L)]$	(3)	α is fitting parameter, and changes with soil type. R is cement to water ratio, K_E is gradient of the linear relationship between modulus and cement to water ratio (c/w) of cement treated soil at 28 days, w_L is liquid limit in situ.
	Zhang et al. (2013)	$q_u(C_m, w, t) = \begin{cases} K_{\mathrm{I}} C_m^{k_3} exp(-k_2 w) & \text{Zone I} \\ K_{\mathrm{II}}(C_m - C_0) exp(-k_2 w) & \text{Zone II} \end{cases}$	(4)	$q_u(C_m, w, t)$ is predicted strength; C_m is cement content，w is water content, C_0 is critical cement content; K_{I}、K_{II}、k_2、k_3 are fitting parameters; Zone I is inactivity zone; Zone II is activity zone.
	Cao and Zhang (2015)	$q_u = a(\frac{n_t}{a_w \lg t})^{-b}$	(5)	a，b are fitting parameters related to soil type，a_w is cement mixed ratio，n_t is void ratio of cement treated soil at t age.
	Xu et al. (2009)	$q_u = [3.4(5a_w)^{\lambda} - 2a_w^{0.75}][1 - exp(-0.025t)] + 2a_w^{0.75} + q_{u0}$	(6)	λ is parameter of in situ soil property，q_{u0} is UCS of in situ soil.
	Horpibulsuk et al. (2005)	$q_u = q_u(28)\left[\frac{w_c / C}{w_{c1} / C_1}\right]^{1.27}(0.039 + 0.283\ln t)$	(7)	$q_u(28)$ is UCS at 28 days under w_c/C condition; w_{c1}/C_1 is water to cement ratio of predict cement treated soil.
	Chu (2005); Liu et al. (2008)	$\frac{q_{u(R,T)}}{q_{u(R_1,28)}} = (-0.019 + 0.31\ln t)\frac{(R - 0.129exp(-0.014w_L))}{(R_1 - 0.129exp(-0.014w_L))}$	(8)	$q_{u(R1, 28)}$ is strength of cement treated soil at 28 days with cement to water ratio of R_1, $q_{u(R, t)}$ is predicted strength at t days with arbitrary cement to water ratio of R.

	Chen et al. (2012)	$\frac{q_u(t_1)}{q_u(t_2)}=\frac{1.3\ln t_1-1}{1.3\ln t_2-1}$	(9)	$q_u(t_1)$ is the predicted UCS at t_1; $q_u(t_2)$ is the tested UCS at t_2.
	Circeo et al. (1962)	$q_u=q_u(t_0)+(k_c\pm 80)\log(t/t_0)$	(10)	k_c is the gradient.
	Mitchell et al. (1972)	$q_u=q_u(t_0)+k_M\log(t/t_0)$	(11)	k_M is the gradient, for granular soil, k_M= 480a_w; for silt and clay, k_M = 70a_w.
without fitting parameters	Yang et al. (2019)	$q_u=q_{ut_0}(\frac{t}{t_0})^R$ $R=\frac{1}{C+\frac{w_n}{(1+w_n)a_w}}$	(12)	q_{ut_0} is the UCS of cement treated soil at the t_0 curing time; w_n is natural water content; a_w is cement mixed ratio; C is water-cement ratio of cement paste, if dry cement powder is used, C = 0.

2. Theoretical development

It is assumed that the relationship between the UCS and age accords with hyperbolic function after 180 days, shown as Eq. (13) and Fig.1.

$$q_u=\frac{t}{a+bt} \quad [13]$$

where, a, b are indefinite parameters; 1/b is asymptote which can be considered as the upper limit of the UCS of the cement treated soil.

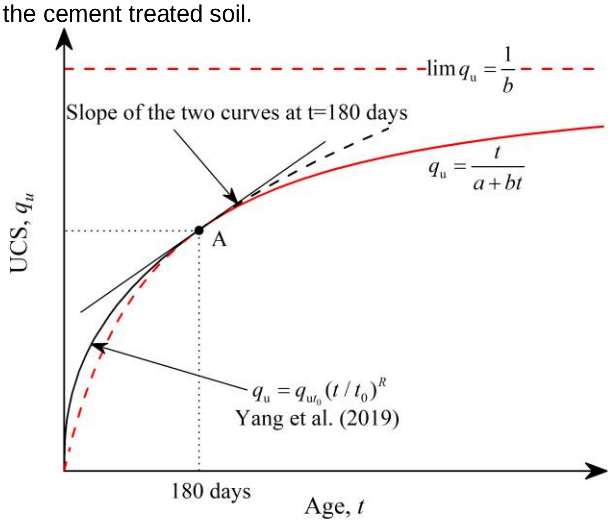

Fig. 1. Schematic of predicted UCS with full age of cement treated soil

Suppose that two curves of Eq. (12) and Eq. (13) connect at t = 180 days (Point A in Fig.1), which means the calculated strengths are equal:

$$q_{ut_0}\left(\frac{180}{t_0}\right)^R=\frac{180}{a+180b} \quad [14]$$

Also, suppose that the increasing rate of the UCS for Eq. (12) and Eq. (13) at point A is same, which means the tangent gradients of two curves are equal at point A:

$$\frac{q_{ut_0}}{t_0^R}R180^{R-1}=\frac{a}{(a+180b)^2} \quad [15]$$

Combine Eq. (14) and Eq. (15) to obtain parameters a and b:

$$a=180^{1-R}R\frac{t_0^R}{q_{ut_0}} \quad [16]$$

$$b=180^{-R}(1-R)\frac{t_0^R}{q_{ut_0}} \quad [17]$$

Then, substitute Eq. (16) and Eq. (17) into Eq. (13) and combine it with Eq. (12) to obtain Eq. (18):

$$\begin{cases} q_u=\frac{q_{ut_0}}{t_0^R}t^R & t\le 180 \\ q_u=\frac{q_{ut_0}}{t_0^R}\cdot\frac{t}{180^{1-R}R+180^{-R}(1-R)t} & t\ge 180 \\ R=\frac{1}{C+\frac{w_n}{(1+w_n)a_w}} \end{cases} \quad [18]$$

Eq. (18) is a formula without fitting parameters for predicting the strength of cement treated soil during full age, and it is an exponential form before 180 days and hyperbolical form after 180 days. The predicted UCS during full age can be obtained by using the UCS, at t0 age and the cement to water ratio R. The asymptote of hyperbolic, namely, the upper limit of the UCS of cement treated soil limqu can be determined by Eq. (19):

$$\lim q_u=\frac{1}{b}=\frac{180^R}{(1-R)t_0^R}q_{ut_0} \quad [19]$$

3. Materials and Methods

The soil used for the test is kaolin, the liquid limit is 33.15%, the plastic limit is 72.09%, the plasticity index is 38.94%, the initial water content is 0.19%, the silt content is 62% and the clay content is 38%. The cement used in the test is 42.5# ordinary Portland cement.

According to the test scheme, the prepared cement soil was loaded into a mould with a diameter of 50 mm and a height of 100 mm. In order to ensure the uniformity of the sample without bubbles, each sample was packed in five layers, and each layer vibrated 10 times. After the sample was prepared, it was stored into the standard curing box (The temperature is 20±1℃, and the humidity > 95%) and curing for 24 hours before demoulding. Then the samples were stored into the standard curing box until reaching the given curing time (Fig. 2).

Fig. 2. Samples in curing

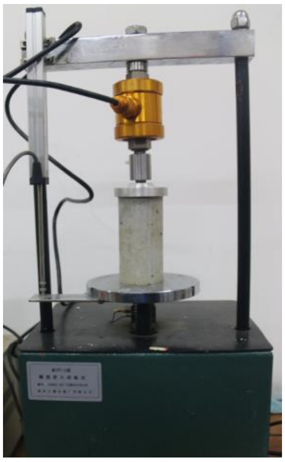

Fig. 3. Unconfined compressive strength test of cement-soil samples with 93.7% water content, 20% cement content and 7 days of curing.

The specimens reaching the age were placed on the test device for unconfined compressive strength test, and lubricant (Vaseline) was applied on the upper and lower pressure plates contacting with the specimens. Fig. 3 is an experimental photograph of unconfined compressive strength test of cement-soil samples with 93.7% water content, 20% cement content and 7 days of curing.

4. Results and Discussions

A lot of researches have been conducted on the relationship of the unconfined compressive strength of cement soil with the water-cement ratio, cement content, and the water content of the original soil. It is generally accepted that within a certain range, the strength of cement soil increases with the rise of cement content, but decreases with the growing water content in original soil and water-cement ratio. Some scholars introduced the concept of cement-water ratio R (the ratio of cement mass to the mass sum of water in soil and cement paste). This parameter comprehensively reflects the impacts of cement content, water content of the original soil and water-cement ratio on the strength of cement soil. Within a certain range, as the cement-water ratio rises, the strength of cement-soil at the same age grows at a faster rate subsequently, which is in line with the growth law obtained from the change of the undetermined parameter b. Table 3 lists test conditions, test results and the predict cement-water ratio *R*'. On this basis, the predict cement-water ratio *R*' and the cement-water ratio *R* are presented in Fig. 4, indicating a good correspondence between *R*' and R.

Fig. 5 is the comparison diagram of forecast strength (forecasted based on the 28d curing time and corresponding strength) and the measured strength of 7d curing time and 90d curing time for cement treated soil. The forecasted value is basically consistent with the measured one.

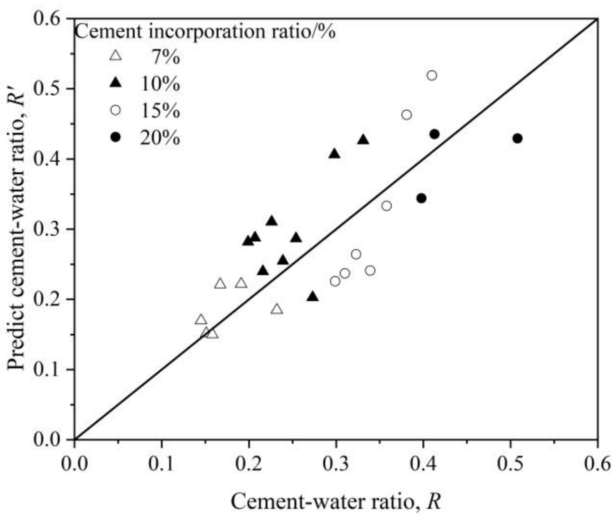

Fig. 4. The relationship between the predict cement-water ratio R' and the cement-water ratio R

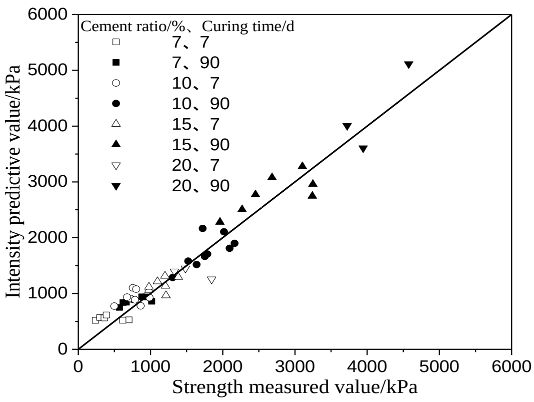

Fig. 5. Comparison between strength forecast value and the measured value

Fig.6 shows the comparison of predicted results and cited experimental results. The experimental data plotted on Fig.6 was adopted from the literature data that contains the age of more than 180 days (Table 2). Circeo proposed a relationship (Eq.10) between the UCS and the age based on the experimental data from cited literatures, the data of silt and clay were cited in this paper. The data of Hayashi et al. was obtained from the core sampling results of soil-cement column formed by dry mixing method. The data of Starcher was the laboratory experimental results of artificial mixed soil (kaolin clay with Nevada sand, 1: 1 ratio by weight). The data of Pham et al. was concerning on clayey sand which the liquid limit is 25% and the plastic limit is 19%.

The calculated results in Fig.6 were obtained from

Table 2. Value of Predicted cement-water ratio R' obtained based on test data

Initial condition		Test result			Cement-water ratio R'
		Curing time/d			
Cement mixed ratio/%	Cement-water ratio *R*	7	28	90	
7	0.232	616	499	439	0.18469
	0.191	701	702	621	0.22175
	0.167	389	774	880	0.22108
	0.158	359	470	588	0.15028
	0.151	300	687	1017	0.15151
	0.145	238	540	894	0.16978
10	0.331	864	1019	1307	0.42620
	0.298	785	1192	1639	0.40628
	0.273	802	1228	1522	0.20299
	0.254	755	1278	1753	0.28667
	0.239	986	1291	1787	0.25469
	0.226	676	1565	2018	0.31041
	0.216	720	1575	1723	0.24000
	0.207	749	1341	2164	0.28774
	0.199	499	1230	2096	0.28216
15	0.410	1214	1901	2454	0.51901
	0.381	979	2072	2683	0.46285
	0.358	1200	2158	3103	0.33312
	0.339	1385	1896	3248	0.24118
	0.323	1096	1702	3241	0.26426
	0.310	1207	1757	3619	0.23687
	0.299	979	2815	3340	0.22585
20	0.508	1332	3588	3414	0.42938
	0.413	1846	2813	4197	0.43522
	0.398	1484	3110	4084	0.34386

partial formulas in Table 1. The formulas of Nagaraj, Yamadera (Eq.1) and Saito, Kitazume (Eq.2) are logarithmic linear fitting curves which exist corresponding conversions between coefficients of each other, and the calculated results is same no matter what the formal differences are. Eqs. (3)-(6) involve some parameters which cannot be determined, such as the gradient of linear relationship between modulus and cement to water ratio, critical cement content C0, porosity of cement treated soil at t age nt and in situ soil characteristic parameter λ etc. Therefore, the above formulas were not adopted. Eqs. (7) and (8) are unable to calculate the results due to lack of UCS of cement treated soil at 28 days in Kitazume's experimental data, therefore, there are no corresponding calculated results in Fig.2. In Eq. (11), it only gives the gradients of granular and fine soils which cannot determine the gradient of artificial mixed soils used in Starcher's experiment, so, Eq. (11) is unable to calculate and there are no corresponding results in Fig.2d).

Among those predicted results, the results of Eq.18, and the fitting formulas of Kitazume et al. (2003); Nagaraj and Miura (1996); Saitoh (1988); Yamadera (1997), are in good agreement with experimental results. The high consistence of the fitting formulas is depending on its nature, fitting, and the form of the formula. However, when the age continues to increase, the predicted UCS increases infinitely with the age due to the form of the formulas. The tendency of increases infinitely is contrary to the basic facts that the strength of soil cement cannot increases infinitely, and the chemical reactions cannot be repeated indefinitely. Besides, the fitting formulas cannot be used to predict unless all the conditions to be predicted are consistent with those to be fitted. The results of the fitted UCS depends on which data that used and the corresponding curing time. Therefore, if the linear fitting is used, the slope and the intercept will be different when the UCS at different curing time is used. The predicted results of the formula proposed in this paper generally reflect the growth law of the UCS of cement treated soil relatively.

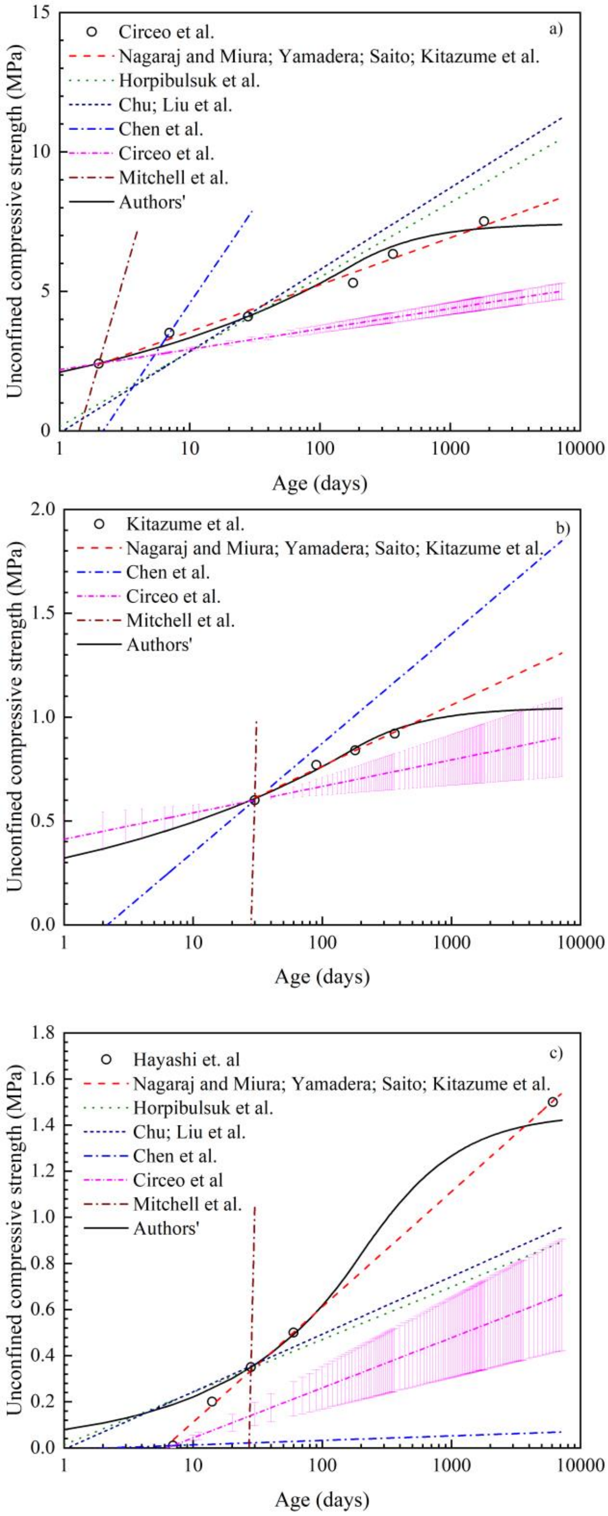

Table 3. Experimental parameters of UCS of cement treated soil

Soil type	Density (g/cm^3)	Water content (%)	Cement content	Longest time (days)	Sample preparation	Literatures
Silt (clayey) soil	1.63-1.84	13.8-18.5	Cement ratio:6 - 30 %	1825	Field	Circeo et al. (1962)
Japan, Kawasaki marine clay	—	160	Cement ratio: 30 %	365	Field	Kitazume et al. (2003)
Japan, Hokkaido clay	1.60-1.70	80-100	290 kg/m^3	6205	Field	Hayashi et al. (2003)
Mixed soil	—	—	R =0.25	433	Lab.	Starcher (2013)
Australian sandy clay	1.68	37.7	120 kg/m^3	384	Lab.	Pham et al. (2017)

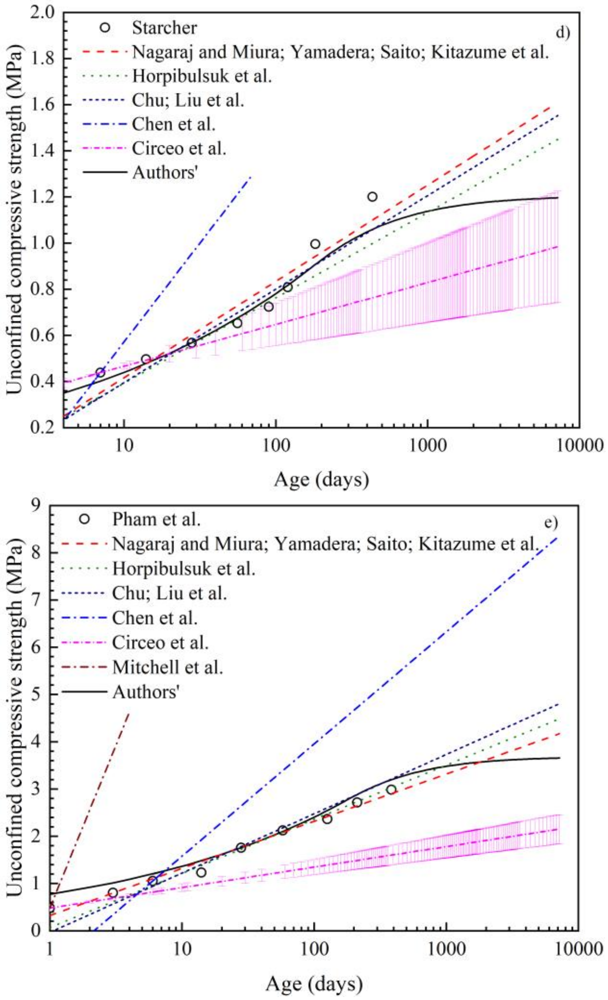

Fig. 6. Comparison between predicted and experimental UCS

5. Conclusions

In this study, A new formula without fitting parameters for predicting full age UCS of cement treated soil has been established based on the proposed relationship between the UCS and the age and the assuming that the UCS increases in hyperbolic law after 180 days. The calculated results of the formulas are consistent with long-term experimental data from cited literatures.

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Symbols and abbreviations

$q_u(t_1)$	Predicted UCS
t	Curing age
$q_u(14)$	UCS at 14 days
a, b	Fitting parameters
α	Fitting parameter, and changes with soil type
R	Cement to water ratio
K_E	Gradient of the linear relationship between modulus and cement to water ratio (c/w) of cement treated soil at 28 days
w_L	Liquid limit in situ
$q_u(C_m, w, t)$	Predicted strength; C_m is cement content，w is water content
C_0	Critical cement content
K_I、K_{II}、k_2、k_3	Fitting parameters, Zone I is inactivity zone; Zone II is activity zone
a_w	Cement factor
n_t	Void ratio of cement treated soil at t age
λ	Parameter of in situ soil property
q_{u0}	UCS of in situ soil
$q_u(28)$	UCS at 28 days under w_c/C condition
w_{c1}/C_1	Water to cement ratio of predict cement treated soil
$q_{u(R1,\ 28)}$	Strength of cement treated soil at 28 days with cement to water ratio of R_1
$q_{u(R,\ t)}$	Predicted strength at t days with arbitrary cement to water ratio of R
$q_u(t_1)$	is the predicted UCS at t_1
$q_u(t_2)$	The tested UCS at t_2
k_c	The gradient
k_M	The gradient, for granular soil, k_M= 480a_w; for silt and clay, k_M = 70a_w
q_{ut0}	The UCS of cement treated soil at the t_0 curing time
w_n	Natural water content
C	Water-cement ratio of cement paste, if dry cement powder is used, C = 0
R'	Predict cement-water ratio