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Unified strength prediction model for cemented soils

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Abstract. Cementation, even in small amounts, tends to alter the mechanical properties of soil significantly. Ordinary Portland Cement (OPC) is a widely used binding admixture, but there has been an increasing need for replacement owing to its carbon footprint. One such alternative is Calcium Sulfoaluminate cement (CSA), which has higher initial strength gain and lower carbon footprint than OPC. Since existing strength prediction models available from literature were developed for conventional cement types such as OPC and Portland Blast Furnace Cement (PBFC), those are not applicable for predicting the strength evolution of soil treated by other types of cements (e.g., underpredicting the initial strength of CSA treated sand). It is because the prediction models available are generally either soil-specific or cement-specific. This paper proposes a unified strength prediction model that works irrespective of cement and/or soil types by introducing a slope parameter that controls time-dependent strength gain. The proposed model is validated by data collected from literature on various soils and cement types. The three-parameter model demonstrates strong applicability for predicting the strength evolution over a wide range of water-to-cement ratios.

Keywords: Calcium sulfoaluminate cement; cement treated soil; ordinary portland cement; strength prediction model

1. Introduction

Cement is one of the most widely used construction materials. The application of cement is vast and essential in the modern construction industry, as it serves as a fundamental component in the creation of structures, buildings, and infrastructure that shape our cities and support our daily lives. Cement's versatility and strength make it a cornerstone of construction, contributing to the durability and sustainability of countless architectural and engineering projects worldwide. The application of cement is not only limited to concrete technology. Cement application to soils is a widely adopted technique in geotechnical engineering, offering several benefits, such as increased strength and stiffness, reduced permeability, and enhanced durability (Horpibulsuk *et al*. 2003, Consoli *et al*. 2007, Subramanian *et al*. 2020, Jumassultan *et al*. 2021, Alzubaidi *et al*. 2023, Karimi and Aghajani 2023, Khan and Ku 2023, Regasa *et al*. 2023, Sagidullina *et al*. 2024). These improved properties have attracted its application for various geotechnical projects, such as slope erosion control measures, road construction to stabilize the subgrade soils, cement mixed soils as a base of retaining walls, and land reclamation.

Harnessing the full potential of cemented soils in construction would require engineers and researchers to predict and understand the strength characteristics of these materials accurately. In practice, a strength prediction model for cemented soils is essential for several reasons: (*i*) Design Optimization: Engineers rely on the strength of cemented soils to design structures that can withstand various loadings and environmental conditions. A reliable prediction model allows for optimizing these designs, resulting in cost-effective and efficient construction projects. (*ii*) Safety and Reliability: Predicting the strength development of cemented soils is crucial for ensuring the safety and stability of structures over the entire construction period and lifetime. Inaccurate strength estimates can lead to structural failures, endangering lives and causing financial losses. (*iii*) Material Selection: The choice of cement type, content, and curing conditions can significantly influence the strength of cemented soils. A prediction model can help engineers select the most appropriate binding materials and methods for a given project, considering both performance and cost. (*iv*) Environmental Impact: Efficient use of cement in construction minimizes its environmental impact, as excessive cement use contributes to carbon emissions. Predictive models can aid in reducing cement consumption while maintaining required strength levels. Several researchers have developed various strength prediction models over the last decade. Table 1 summarizes the existing strength prediction models compiled from the literature review.

Although strength prediction models have their advantages, it should be noted that, in general, prediction models require an extensive database of test results, which may not always be readily available. Some prediction

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Table 1 Summary of selected existing strength prediction models from the literature review (modified after Subramanian *et al.* 2019)

Reference	Prediction equation	Soil type	Cement type
Abrams (1918)	$q_u = \left(\frac{X}{Y^{w/c}}\right)$	Nil	OPC
Mitchell *et al.* (1974)	$q_{u,T2} = q_{u,T1} + K \times log(\frac{T2}{T1})$	Clay	OPC
Nagaraj *et al.* (1998))	$\frac{q_D}{q_{14}} = a + b\, ln(D)$	Inland Clay	OPC
Kaniraj and Havanagi (1999)	$q_t = q_{t0} + (t/mt + c)$	Silt and Sand	Fly-ash
Horpibulsuk *et al.* (2003)	$\left(\frac{q_{w/c_{1,D}}}{q_{w/c_{28}}}\right) = B^{[w/c_{28} - w/c_D]} \times (X + Y \times ln\, D)$	Marine and Inland Clays	OPC
Lorenzo and Bergado (2004)	$q_u = Ap_a e^{B\left(\frac{e_{ot}}{A_w}\right)}$	Bangkok Clay	OPC
Lee *et al.* (2005)	$q_u = q_0 \frac{e^{m(s/c)}}{(w/c)^n}$	Singapore Marine Clay	OPC
Ahnberg (2006)	$q_u = R \times ln(t)$	Clay	OPC
Consoli *et al.* (2007)	$q_u = A \times C + B$	Sand	OPC Type III
Consoli *et al.* (2010)	$q_u = A \times (C)^B$	Sand	OPC Type III
Xiao *et al.* (2014)	$q_u = q_\infty \left\{1 - \frac{1}{1 + \left(\frac{\alpha t}{q_\infty}\right)^r}\right\} \left\{\frac{exp\left(m\left(\frac{1}{A_w}\right)\right)}{\left(\frac{w}{c}\right)^n}\right\}$	Singapore Marine Clay	OPC
Chian *et al.* (2015)	$q_u = \left(\frac{X}{Y^{w/c}}\right) \times ln(t)$	Singapore Marine Clay	PBFC
Subramanian *et al.* (2019)	$q_u = \left(\frac{X}{Y^{w/c}}\right) \times ln(a \times t)$	Sand	OPC & CSA
Yao *et al.* (2020)	$\ln(q_u) + n \cdot \ln\left(\frac{w}{c}\right) = \ln(q_0) + m\left(\frac{s}{c}\right)$	Clayey soils	OPC
Bi and Chian (2021)	$q_u = \left(\frac{X}{Y^{w/c}}\right) \times 0.5 \times \left[1 + erf\left(\frac{ln(t) - \mu}{\sqrt{2}}\sigma\right)\right]$	Kaolin clay	OPC & PBFC

Note: $q_{u,T1}$ and $q_{u,T2}$ = strength at age *T*1 and *T*2 respectively, q_D and q_{14} = strength at age *D* and 14 days respectively, *t* = curing time, q_t= strength at age *t*, $q_{w/c_{1,D}}$ is the strength of the sample with water-to-cement ratio $(w/c)_1$ after *D* days of curing, $q_{w/c_{28}}$ is the strength of the sample with water-to-cement ratio (*w/c*) after 28 days, q_u= strength of cement soil, p_a = atmospheric pressure, A_w and *C* = cement content, *s/c* = soil-to-cement ratio, and *K*, *a*, *b*, *m*, *c*, *X*, *Y*, *A*, *B*, q_0, *R*, α, *r*, q_∞= fitting constants. μ and σ are mean and standard deviations. OPC = Ordinary Portland Cement, CSA = Calcium sulfoaluminate cement, PBFC = Portland Blast Furnace Cement

models can be complex and challenging to implement in practical engineering applications. The strength of cemented soils can vary due to factors such as curing conditions and soil composition, making prediction models subject to inherent uncertainties. For example, Table 1 shows that the models proposed by Lee *et al.* (2005), Lorenzo and Bergado (2004), and Consoli *et al.* (2007) do not consider the effect of curing time. In contrast, the models that account for the impact of curing time tend to perform well, particularly for cemented clay, although they present inherent complications in their practical applications. This paper aims to thoroughly explore these aspects in-depth and contribute to the ongoing re-search in cemented soil engineering by addressing the data requirements, model complexity, and practical usability of the developed prediction model in real-world engineering projects. Finally, a new unified strength prediction model will be proposed.

2. Strength prediction model of cemented soil

2.1 Problems in strength prediction

To illustrate the need for developing a promising strength prediction model, herein one recent experimental study is first introduced, which showed the significance of the effect of time-dependent strength evolution depending on different cement types. It is noted the reported database is also included in the analysis of the current study later. Subramanian *et al.* (2019) conducted extensive experiments to quantify the strength development of CSA-treated sand. OPC-treated sand with similar water and cement contents was used as a baseline case for comparing the strength of CSA-treated sand. The study used sand with D_{10} and D_{50} of 0.45 mm and 0.71 mm, respectively. The coefficient of curvature (C_C) and coefficient of uniformity (C_U) of sand were 1.00 and 1.78, and the specific gravity of sand was 2.65.

The sand is classified as poorly graded ‘SP’ according to the Unified Soil Classification System (USCS). As cementitious binding materials, Ordinary Portland Cement Type I, which primarily comprises Alite and Belite (87.3% of total cement), and Calcium sulfoaluminate cement (CSA), which comprises ye’elimite and gypsum, were used for cement-treated samples in the study.

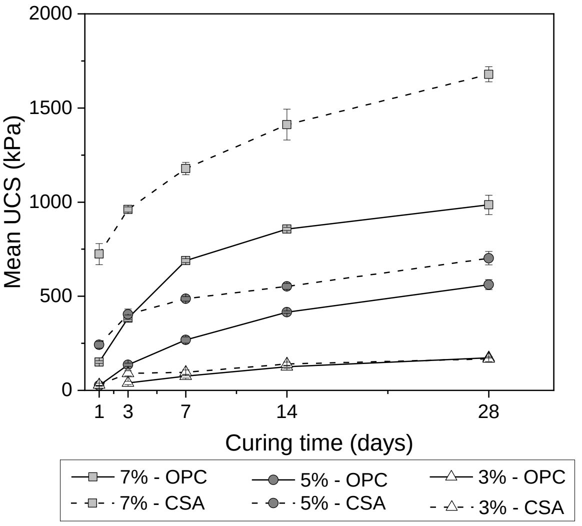

Fig. 1 Comparison of unconfined compressive strength development with curing time for OPC and CSA-treated sand (revised from Subramanian *et al.* 2019)

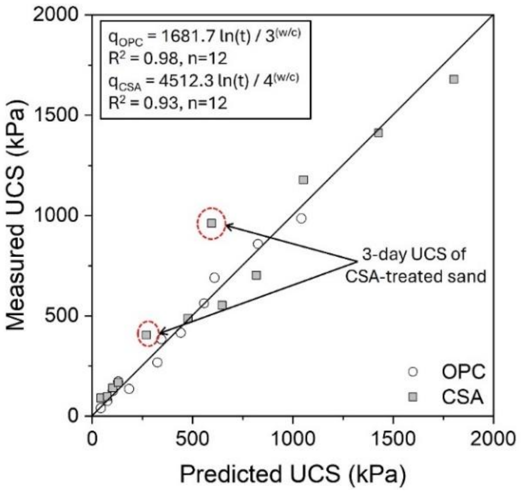

Fig. 2 Predicted strength vs measured strength for OPC and CSA-treated sand using Chian *et al.* (2015) prediction equation

The experimental program consisted of a series of unconfined compression tests to study the effect of cement content and curing time on both OPC and CSA-treated sand. It is worth noting that unconfined compression testing is less time-consuming, reliable, and economically feasible. Moreover, the unconfined compressive strength is a good measure of the effectiveness of cementation. The cement contents considered in the study were 3%, 5%, and 7%, and the curing times considered were 1, 3, 7, 14, and 28 days. Five samples were prepared for each batch, and unconfined compressive testing was carried out at a rate of 1mm per minute according to ASTM standard (ASTMD2166/D2166M-24, 2024).

Fig. 1 shows the variation of unconfined compressive strength with curing time for various cement contents. After the five samples were tested, the average value was calculated based on three samples whose coefficient of variation was less than 10%. The strength varies hyperbolically with time for both OPC and CSA-treated sand. However, the strength obtained by the CSA-treated sand is always higher than that of the OPC-treated at a given cement content and curing time. For 7% cemented sand, OPC attains 15% of the ultimate strength (i.e., assumed strength at 28 days) in one day, while CSA obtains 43% of the ultimate strength in one day.

This rapid strength development for CSA-treated sand is attributed to the hydration of ye'elimite in the presence of gypsum to form ettringite (Winnefeld and Barlag 2010, Winnefeld and Lothenbach 2010, Subramanian *et al.* 2018). In the long term, the hydration of belite forms calcium silicate hydrate (CSH), and the ettringite gets converted to monosulfate. In the case of OPC-treated sand, the formation of calcium aluminate hydrate (CAH) is controlled by anhydride, which results in slow initial strength gain. With time, more anhydrous cement gets exposed to water to form calcium silicate hydrate (CSH), which is responsible for long-term strength.

Abrams (1918) highlighted that the water-to-cement ratio is the only strength governing parameter for cemented materials and proposed the earliest strength prediction model as follows

$$q_u = \frac{X}{Y^{(w/c)}} \tag{1}$$

where q_u is the compressive strength of cemented material, w/c is the water-to-cement ratio, and X and Y are the empirical constants. Subsequently, several prediction models have been proposed to predict the strength of the cemented soil. Especially, Chian *et al.* (2015) proposed an updated strength prediction model for cement-treated clay by modifying Eq. (1) to reflect the effect of curing time.

$$q_u = \left(\frac{X}{Y^{(w/c)}}\right) \times \ln(t) \tag{2}$$

where 't' is the curing time. The empirical constant X was defined in relation to the soil-to-cement ratio (s/c), while the Y parameter was determined to be dependent on the soil type. Herein, this model is explored to estimate the strength of OPC and CSA-treated sand. Fig. 2 shows the applicability of Eq. (2) to predict the strength of cemented sand. Although the coefficient of determination (R^2) values are above 0.9, the CSA-treated sand shows a much higher root mean square error (RMSE) value, which indicates that the model works for OPC-treated sand, while some scattering is observed for CSA-treated sand. The deviated prediction in Fig. 2 corresponds to the early curing strength of the CSA-treated sand due to its rapid strength development. The rapid strength-gaining behavior of CSA-treated sand cannot be properly captured by the model. The predicted 3-day strength of 7% CSA content in sand was almost 50% lower than the actual strength of CSA-treated sand.

The model proposed by Chian *et al.* (2015) works well for OPC-treated sand (empirical constant Y depends on soil type) but does not give good predictions for the strength of soils improved with rapid strength-gaining cement. For OPC and PBFC-treated soils, the slope of the normalized

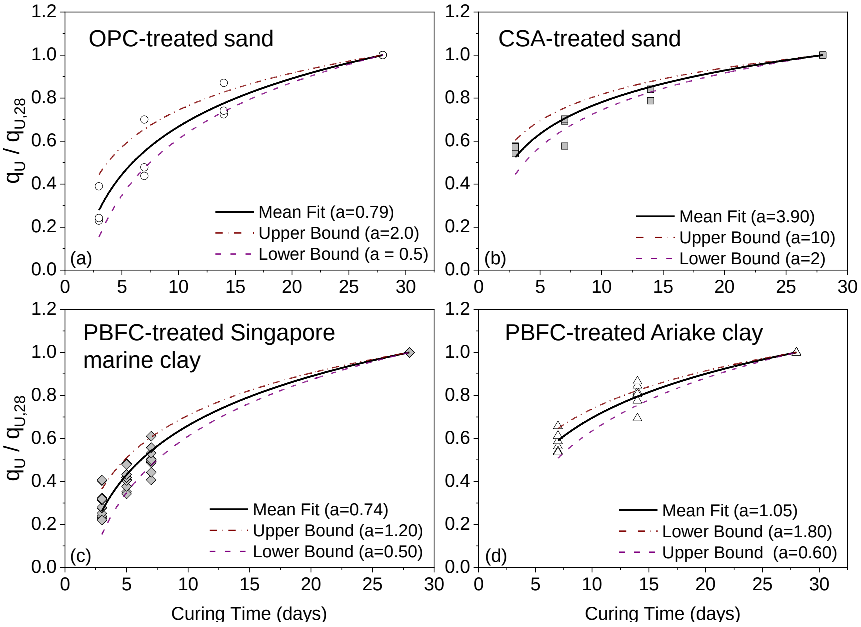

Fig. 3 Plots of $q_u/q_{u,28}$ vs curing time to determine slope parameter 'a' for the database collected from (a) OPC-treated sand (data from Subramanian *et al.* 2019), (b) CSA-treated sand (data from Subramanian *et al.* 2019), (c) PBFC-treated Singapore Marine Clay (data from Chian *et al.* 2015) and (d) OPC-treated Ariake Clay (data from Horpibulsuk *et al.* 2003)

compressive strength, defined as the ratio of strength at any curing time to the strength at 28 days of curing, aligns with the fixed form $\ln(1 \times t)$, which is consistent with the equation proposed. In the model, the initial strength is underpredicted when used to predict the strength of a rapid strength-gaining cement. For rapid curing cement, the ratio of strength at any curing time to the strength at 28 days of curing does not follow the $\ln(1 \times t)$ pattern. Hence, Subramanian *et al.* (2019) proposed a strength prediction model to reflect the different characteristics of time-dependent strength development based on the soils treated by various binding admixtures. A database was also compiled from published sources to confirm the applicability of the model for different soil and cement types.

2.2 Model calibration using slope parameter

As discussed earlier, the function $\ln(1 \times t)$ would be able to predict the strength of conventional OPC and PBFC-treated soils for various curing times. To improve the flexibility of the prediction model, Subramanian *et al.* (2019) considered a coefficient within the natural logarithmic function, which is called the slope parameter. CSA cement shows a higher initial strength development than OPC. Hence, the slope parameter is not fixed to one, which means the function can be easily modified as $\ln(a \times t)$. Thus, the new model was proposed as follows

$$q_u = \left(\frac{X}{Y^{(w/c)}}\right) \times \ln(a \times t) \tag{3}$$

where 'a' is the slope parameter to reflect the time- terms of normalized strength (e.g., normalizing by 28 days dependent strength development. If Eq. (3) is expressed in strength), it is possible to remove other influencing parameters and isolate the slope parameter only. In addition to the strength at 28 days, the strength of cemented soils needs to be examined for at least two other curing times to accurately obtain the slope parameter.

$$\left(\frac{q_u}{q_{u,28}}\right) = \frac{ln(a \times t)}{ln(a \times 28)} \tag{4}$$

The slope parameter can be determined by fitting Eq. (4) to a plot of normalized strength against curing time, as depicted in Fig. 3. To account for data variability, upper and lower bounds are established together. For OPC and CSA-treated soils, the slope parameter ranges approximately between 0.79 and 3.90. The best-fit slope parameter for OPC (0.79) is much lower than CSA (3.90). Thus, the slope parameter provides insight into the rate of initial strength development but does not influence the ultimate strength of the cemented soil.

The slope parameter 'a' is primarily influenced by the rate of initial strength development, which is determined by the hydration reaction between the binding agent and the host soil. Additionally, this parameter is affected by secondary factors, including curing temperature and curing conditions (whether wet or dry). Therefore, the rate of strength evolution can be indirectly inferred from the slope parameter. It serves as an indicator to distinguish the rapid strength-gaining types of cement and typical cement types like OPC.

Using the compiled database from the literature, Fig. 4 shows the comparison between measured strength and predicted strength using Eq. (3) for various types of cement-treated soils. The results of the study are summarized in

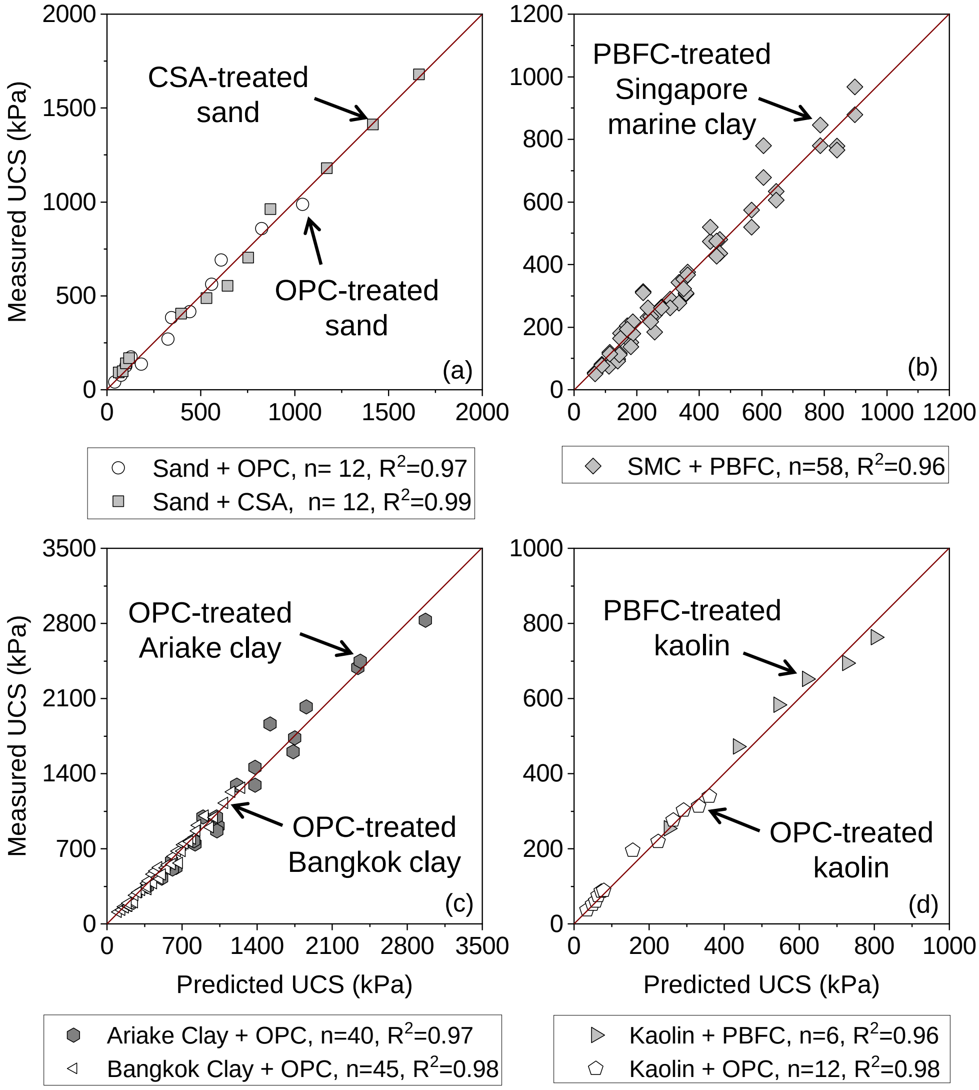

Fig. 4 Comparison between measured strength and predicted strength for various cemented soils using the model proposed by Subramanian *et al*. (2019): (a) OPC and CSA treated sand, (b) Singapore Marine Clay with PBFC (data from Chian *et al*. 2016) and (c) Ariake Clay and Bangkok Clay with OPC (data from Horpibulsuk *et al*. 2010) and Uddin *et al*. 1997) and (d) Kaolin with OPC and PBFC (data from Flores *et al*. 2010)

Table 2 Summary of results for the prediction model by Subramanian *et al*. (2019)

S. No.	Reference	Material	Cement	a	X	Y	R²
1.	Subramanian *et al*. (2019)	Sand	OPC	0.79	1848.1	3.00	0.97
2.	Subramanian *et al*. (2019)	Sand	CSA	3.90	2954.7	4.00	0.99
3.	Uddin (1994)	Bangkok Clay	OPC	1.28	608.69	1.27	0.98
4.	Horpibulsuk *et al*. (2003)	Ariake Clay	OPC	1.05	2521.5	1.22	0.97
5.	Flores *et al*. (2010)	Kaolin Clay	OPC	0.70	600.57	1.30	0.98
6.	Flores *et al*. (2010)	Kaolin Clay	PBFC	0.37	1620.60	1.30	0.96
7.	Chian *et al*. (2016)	Singapore Marine Clay	PBFC	0.74	2578.90	1.30	0.96

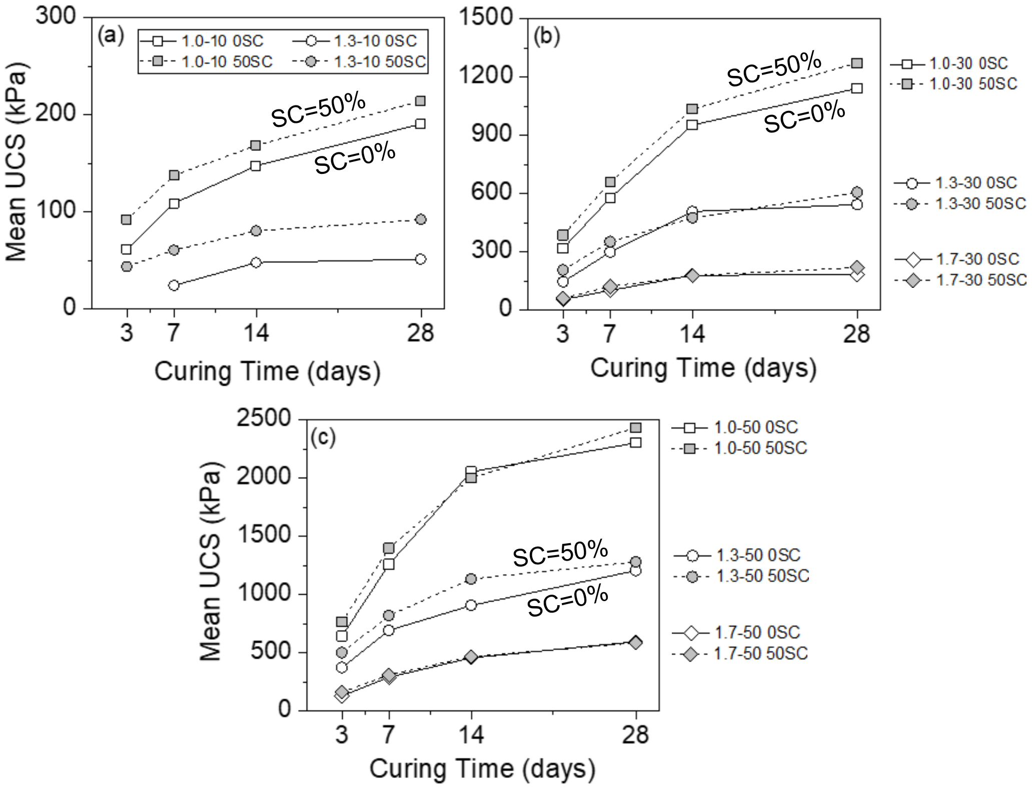

Fig. 5 Development of unconfined compressive strength with curing time for (a) 10% CC, (b) 30% CC, and (c) 50% CC. Note: The legend 1.0-10 50SC indicates w^* equal to 1.0 times the liquid limit of kaolin clay, which is 80%, 10% CC, and 50% SC

Table 2. It was demonstrated that the proposed model can accurately predict the measured values from the laboratory tests for various cemented soils, despite the limited information available.

3. Development of unified strength prediction model

3.1 Applicability of Subramanian et al. (2019) prediction model to cemented binary mixtures

All the above laboratory tests and the database collected were based on samples of pure clay or pure sand. However, in-situ is seldom homogenous and often has a mix of clay and sand. While clay is a cohesive material whose strength depends primarily on the water content, sand is a granular material that does not have the water retention capacity of clayey soils. Since water is also consumed during the hydration of cement, the amount of water in a cemented binary mixture plays an important role in governing its overall behavior. Building on this, Subramanian and Ku (2023) proposed a framework to investigate the effects of sand mixed with cement-treated clay, treating the sand as an impurity within the mixture. Hence, the mix terminologies were modified to accommodate the presence of sand. The sand content (SC) was defined as the ratio of the mass of dry sand (M_{sa}) to the mass of soil ($M_{sa} + M_{clay}$). The cement content (CC) was defined as the ratio of the mass of cement (M_c) to the mass of dry clay (M_{clay}), while water content (w^*) is defined as the ratio of the mass of water (M_w) to the mass of the sum of dry clay (M_{clay}) and cement powder (M_c). These terminologies are modified from those of the conventional definition of cemented soils. It is because these definitions of cement and binding water content allow the same water-to-cement ratio to be maintained for both cemented clay and cemented sandy clay. The sand contents (SC) varied between 0% and 50%. For the rationale behind the adopted terminologies, refer to Subramanian and Ku (2023).

Then, a parametric study was carried out with a sand content (SC) of 0% and 50%. Three water contents (w^*), 80%, 105%, and 140%, were used, which correspond to approximately 1.0, 1.3, and 1.7 times the liquid limit of kaolin clay, respectively. Three cement contents (CC) were used (10%, 30%, and 50%), and curing times (t) of 3, 7, 14, and 28 days were adopted. Ordinary Portland Cement (OPC) was used as binding admixture for this study. Fig. 5 illustrates the evolution of strength (q_u) with curing time for all the mix ratios considered by Subramanian and Ku (2023). Cemented sandy clay exhibits greater strength compared to cemented clay, irrespective of cement content, water content, and water-to-cement ratio. The inclusion of sand grains provides extra resistance to the formation of shear planes, thereby enhancing q_u.

In this study, the applicability of Eq. (3) (the model proposed by Subramanian *et al.* 2019) is further examined by applying the fitting equation to the data obtained by Subramanian and Ku (2023) for cemented clay and

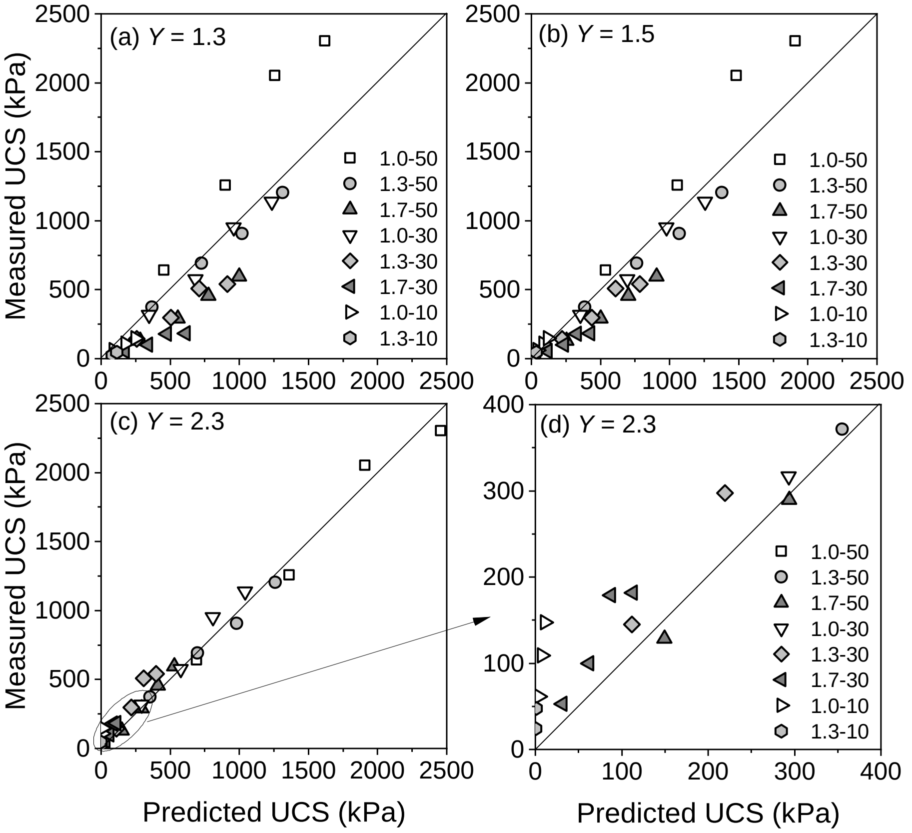

Fig. 6 Measured UCS vs predicted UCS using the model proposed by Subramanian *et al.* (2019) with different "Y" values, (a) Y=1.3, (b) Y=1.5, (c) Y=2.3, and (d) Y=2.3 (enhanced scale). Note: The legend 1.0-50 indicates water content equal to 1.0 times the liquid limit of kaolin clay, which is 80%, and cement content of 50%

cemented sandy clay. Since kaolin clay is used, the starting value of fitting parameter "Y" is taken as 1.3, as suggested by Chian *et al.* (2016). Figure 6a shows the prediction result using the commonly used value for the fitting parameter "Y" of 1.3. The model overpredicts the strength of samples for the lower water-to-cement ratio (2.34). This discrepancy could be due to the latter being outside the range of water-to-cement ratios considered in Subramanian *et al.* (2019)'s database.

Figs. 6(b) and 6(c) show the applicability of the model when the fitting parameter "Y" values are 1.5 and 2.3, respectively. As the "Y" value increases, the model tends to underpredict the strength value at a higher water-to-cement ratio. The fitting parameter "Y" is less dependent on the soil type and more dependent on the water-to-cement ratio. Based on the parametric investigation, the model's performance appears to be less reliable when applied to cemented binary mixtures.

3.2 Enhanced model for unified strength prediction

It was noted that the water-to-cement ratio plays a crucial role in determining the strength of cement-treated clay. Thus, to improve the model, we conducted a more straightforward investigation by normalizing the strength by the curing period and then plotting it against the water-to-cement ratio (shown in Fig. 7). It is observed that an inverse power relationship exists between the normalized strength and the water-to-cement ratio, thus a new, more intuitive model is proposed as follows

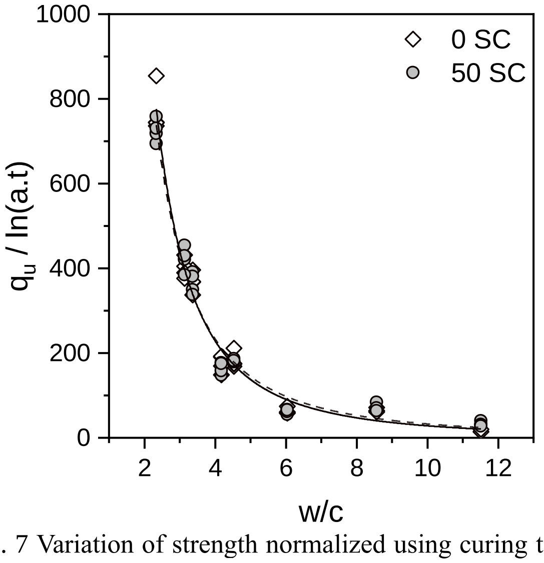

Fig. 7 Variation of strength normalized using curing time vs. water-to-cement ratio

$$q_u = \frac{X}{(w/c)^m} \times \ln(a \times t) \tag{5}$$

In Eq. (5), the fitting parameter 'a' controls the rate of change of strength with curing time, and the fitting

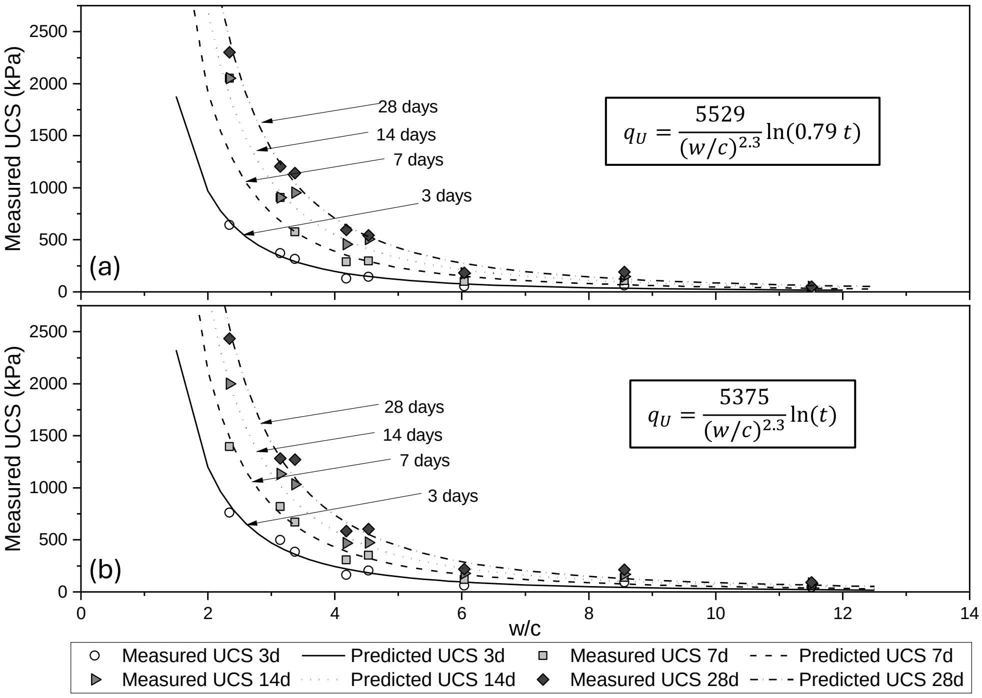

Fig. 8 Measured UCS vs predicted UCS using the model proposed in this study (a) cemented clay and (b) cemented sandy clay

Table 3 Summary of the parameters of the proposed model

Reference	Soil Type	Cement	a	m	X
Subramanian *et al.* (2019)	Sand (SP)	OPC	0.79	2.56	1128
		CSA	3.90	2.79	1200
Uddin *et al.* (1997)	Bangkok Clay	OPC	1.28	1.40	1633
Horpibulsuk *et al.* (2010)	Ariake Clay	OPC	1.52	1.05	10710
Chian *et al.* (2016)	Singapore Marine Clay	PBFC	0.74	2.86	131482
Subramanian and Ku (2023)	Kaolin Clay	OPC	0.79	2.30	5529
	Kaolin clay + sand	OPC	1.0	2.30	5375

parameter 'm' controls the dependency of strength on the water-to-cement ratio. Fig. 8 shows the robust applicability of the model in predicting the strength of both cemented clay and cemented sandy clay. The values of (a, m,X) for cemented clay and cemented sandy clay are (0.79, 2.3, 5529) and (1.0, 2.3, 5375), respectively. The model gives a good prediction of the strength of cemented soils with R^2 of 0.97. It should be noted that parameter 'm' is a constant, irrespective of cement or water content.

3.3 Applicability of unified prediction model to other soils and cement types

The applicability of the proposed model is verified by predicting the strength of other soils (sand, clay) and cement types (OPC, PBFC, CSA). For this purpose, the unconfined compressive strength data is collected from the literature, and the adopted parameters are summarized in Table 3.

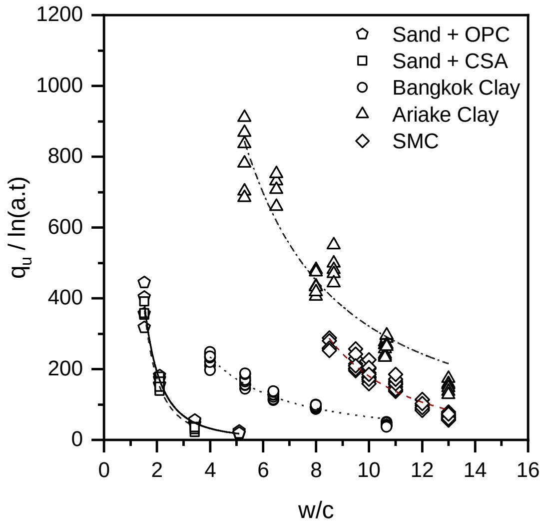

Fig. 9 Variation of normalized strength using curing time vs. water-to-cement ratio for the data collected from the literature

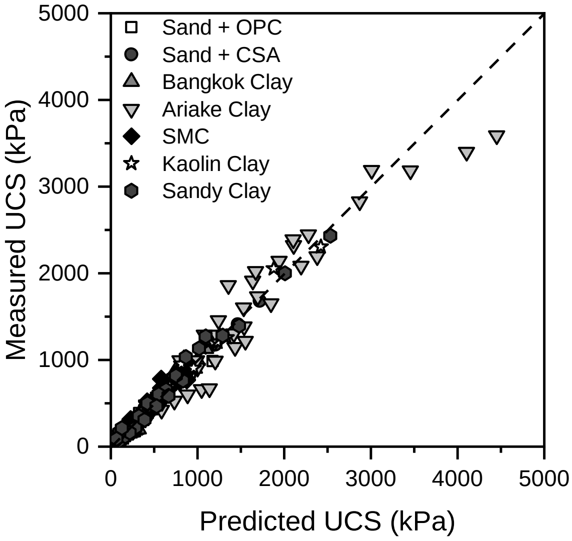

Fig. 10 Predicted strength vs measured strength for the data collected from the available literature (i.e., Table 3)

Fig. 9 shows the plot of normalized strength against the water-to-cement ratio for the data collected from the literature. All the data present strong inverse relationships between the normalized strength and the water-to-cement ratio. The proposed model is designed for geotechnical ground improvement, which typically involves high water-to-cement ratio ranges. In the future, the model can be further calibrated for applicability in lower water-to-cement ratio ranges. Fig. 10 shows the plot between predicted and measured strength values. The high value of fitting parameter 'X' for Singapore marine clay could be because the testing has been carried out over a narrow range of water-to-cement ratios.

Based on the proposed model, design recommendations are given to achieve a good prediction of strength as follows:

(a) The unconfined compressive strength should be known for at least three different curing times to get a reasonable estimate of the slope parameter.
(b) For clayey soil, the unconfined compressive strength should be obtained at least for three water-to-cement ratios, and the latter should vary over a wide range.
(c) The minimum curing time adopted for proposing and validating the model is 3 days. More data is required for curing times less than 3 days to validate the model for earlier strength predictions.

The enhanced model in this study showed an ability to reasonably capture the strength development of cemented soils regardless of cement and soil types. In the future, more data may be needed to further refine the model by varying the water and cement content over a wider range. This would allow the exponent 'm' value to be expressed as a function of cement or water content.

4. Conclusions

The strength prediction models are useful for predicting the strength of cement-treated soils with limited design information. However, existing prediction models developed for OPC-treated soil could not reasonably estimate the strength development of eco-friendly and high initial strength-gaining cement, such as calcium sulfoaluminate cement. As one of the most robust models, this paper first reviewed the prediction model proposed by Subramanian *et al.* (2019), which was recently developed for forecasting the strength of various types of cement and soils. Subsequently, its applicability was thoroughly examined.

When the prediction model was applied to the cemented binary mixtures, it did not correctly forecast the strength development of the binary mixtures. The water-to-cement ratio of the cemented binary mixture was outside the range of the validated data used by Subramanian *et al.* (2019). Eventually, this paper proposed a new unified strength prediction model that can be used for various cemented soils with a wide range of water-to-cement ratios. The enhanced model was successfully validated using the data collected from various sources in the literature for different soil and cement types.

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