Study on the Application of the Concrete Model in PLAXIS to Bangkok Clay improved with Portland Cement

Soe Thinzar Than[1,*] and Pongpipat Anantanasakul[2]

[1,2] *Department of Civil and Environmental Engineering, Faculty of Engineering, Mahidol University, Nakhon Pathom, THAILAND*
**Corresponding author; E-mail address: soe.tha@student.mahidol.ac.th*

Abstract

Ground improvement by admixing the natural soil with Portland cement is one of the effective soil treatment techniques to improve the engineering properties of soft Bangkok clay. The objective of this study is to investigate the application of the Concrete Model in PLAXIS for cement-treated Bangkok clay. The Concrete Model is a constitutive model which has the features to simulate the non-linear behavior of cementitious materials both in the hardening and softening regimes. This study presents the formulation and calibration of the Concrete Model, particularly for cement-treated cohesive soils. The time- independent strength and stiffness parameters for the Concrete Model are calibrated from the laboratory unconfined compression tests and undrained triaxial compression tests of cement-treated Bangkok clay. The relationships between the undrained stiffness and shear strength parameters and cement content and water-cement ratio are discussed. The applicability of the Concrete Model for cement treated Bangkok clay is assessed. The SoilTest feature in PLAXIS finite element software is employed to calibrate the relevant model parameters. Parameter values for the Concrete Model and laboratory experiments that result in accurate simulation of the behavior of cement-treated Bangkok clay are provided and discussed.

Keywords: Cement-treated, Bangkok Clay, Concrete Model, PLAXIS

1. Introduction

The Bangkok Metropolitan region in Thailand is a hub for major construction projects in the Bangkok Plain, also known as the Lower Central Plain, which is situated near the Gulf of Thailand. The Bangkok Plain was once a shallow marine sea, and over time the deposited sediments transformed into soft clay, known as Bangkok soft clay. This type of clay is characterized by a thick layer of soft to very soft clay with low compressibility and high-water content. The presence of this soft clay has led to challenges in foundation and deep excavation works. To address these challenges, the construction industry has widely implemented soil-cement treatment technology to increase the strength and stiffness of the native soft soil. Popular methods for mixing soil-cement include grouting and deep soil mixing. The addition of cement can significantly improve the engineering properties of problematic soft soil, leading to a new soil-cement formation with higher strength and lower compressibility.

The deep mixing method was originally developed in Japan during the late 1960s and was first applied for practical use in the mid-1970s. Since then, it has been widely used in other countries in Asia and beyond for various purposes, including enhancing the bearing capacity of foundation soils, improving stability, reducing settlement, and supporting excavation. The method involves the addition of a binder material to in-situ soil to form a soil-binder mixture or column, which improves the strength and stiffness of the soil. The characteristics of the improved soil-cement formation are dependent on several factors, including the properties of the soil, the mixing method, and the features of the binder material. Commonly used binder materials include cementitious materials such as lime or cement, which can be introduced into the ground in either wet or dry form. Among those, the soil-cement is a mixture of in situ soil, Portland cement and water.

In the context of deep cement mixing ground improvement works, numerical methods are commonly used to simulate potential deformation and stability behaviors, such as in embankment, foundation, and retaining structures. To perform finite element analysis, an appropriate constitutive model that accurately represents the key behavior of soft ground after improved by hydration and pozzolanic reactions between soil and cement is essential for achieving satisfactory deformation of foundation and stiffness increment of the improved ground. Finite element analysis has been widely used to simulate the behavior of cement-admixed soil in deep mixing works. From literatures, the elasto-plastic models with strain softening and hardening features were employed to simulate the axial and lateral stress distribution, the settlement, and the slope stability of embankment. Among the different types of constitutive models, the Mohr-Coulomb model was commonly practiced in simulating the behavior of cement-admixed soil in aforesaid simulation according to existing studies. However, the development of tensile stress in the cement-admixed material is also a significant problem and unavoidable in real practice. Excessive tensile stress can lead to crack formation and failure in the cement-admixed material. Therefore, precise advanced constitutive models are crucial for predicting crack formation, deformation, and stress distributions in better accuracy. The adoption of advanced models for simulating the behavior of cement-treated ground is still limited due to the challenges in parameter calibration and the need for extensive experimental work to derive the necessary parameters of the model.

In geotechnical applications, a linear elastic approach is commonly utilized to model nonlinear composite materials, such as concrete elements, due to their high stiffness in comparison to the native soil properties. The Concrete Model was introduced as a material model, following the Shotcrete material model, to enhance its capabilities. Initially, the Shotcrete model was implemented in the finite element software PLAXIS 2D to provide a more realistic representation of shotcrete linings. Although the Shotcrete model was primarily designed for modeling shotcrete behavior, it has also demonstrated its usefulness in other geotechnical applications, such as soil improvements, soil reinforcement, and concrete structures, including piles, beams, and retaining walls. Since the release of PLAXIS 2D 2018, the Concrete Model has been included in the standard material library and is considered the most effective standard model for modeling concrete elements in PLAXIS [25]. Advanced constitutive models based on the bonded soil framework have been developed in the literature for cement-treated soils. In this study, the Concrete Model was employed for cement-treated Bangkok clay to investigate the applicability of Concrete material model behavior in cement-treated soil in deep mixing work. In this study, the behavior of cement-treated Bangkok clay was simulated by employing the Concrete Model in PLAXIS 2D and presented the comparison of stress-strain relationships between the results of simulation by the Concrete Model and the experimental results from previous literatures.

2. Constitutive Model for Soil-Cement

2.1 Concrete model

The Concrete Model was initially created to simulate shotcrete behavior, but it has proven to be beneficial in other areas such as soil reinforcement, soil improvement (e.g., jet grouting columns), and concrete structures (e.g., beams). For concrete structure elements, a linear elastic material model is typically utilized because of their strength compared to soil. However, in certain geotechnical problems, a reliable stress-strain redistribution in the continuum is necessary to correct the design, particularly in the complex non-linear behavior of concrete structures. The complex behavior of concrete includes limited strength in compression and tension, time-dependent strength and stiffness, strain hardening/softening, creep, and shrinkage. Currently, the numerical engineering approach for simulating the shotcrete lining in tunnel construction employs the linear elastic material model. Although simulating the shotcrete lining in tunnel construction using a linear elastic material model can produce a realistic deformation of the shotcrete lining, it often results in lining stresses that are excessively high when subjected to significant bending. By using the Concrete Model, a more realistic stress distribution can be achieved as the material's non-linearity is considered, resulting in more accurate stress calculations which is able to simulate concrete's time-dependent strength and stiffness, strain hardening-softening in compression and tension, as well as creep and shrinkage [16].

2.2 Model structure

2.2.1 Formulation of the Concrete model

The Concrete Model is an elastoplastic model that can simulate the time-dependent behavior of concrete, including strain hardening-softening in both compression and tension, as well as creep and shrinkage. Initially developed to model shotcrete behavior in PLAXIS 2D, the Concrete Model has also been applied to simulate the non-linear behavior of cementitious materials in soil reinforcement, such as soil-cement columns, and soil improvement works.

The Concrete Model considers the reduction in stiffness behavior after cracking brittle cemented materials and can simulate both time-dependent and time-independent behaviors. Time-dependent properties include time-dependency strength, stiffness, creep, and shrinkage of concrete material under strain hardening-softening conditions in compression and tension. Time-independent properties include the normalized strength and stiffness of cured concrete at a certain time of hydration. Consequently, the total strain in the Concrete Model can be decomposed into elastic, plastic, creep, and shrinkage strains.

$$\varepsilon = \varepsilon^{e} + \varepsilon^{p} + \varepsilon^{cr} + \varepsilon^{shr} \qquad (1)$$

2.2.2 Yield surfaces of the Concrete model

The yield surfaces in the soil models represent the variation of stress states according to the change of strains. In the formulation of the Concrete Model, two separate yield surfaces based on the Mohr-Coulomb failure criterion for compression and Rankine failure surface for tension are adopted (Fig.1).

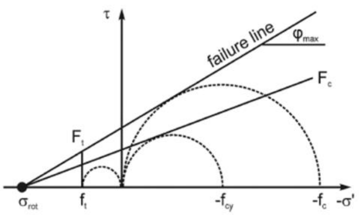


Fig. 1 Yield surfaces and failure envelope for Concrete Model

The yield functions for compression (F_c) and tension (F_t) can be formulated in terms of principal stresses related to the uniaxial compressive yield stress (f_{cy}), and the uniaxial tensile yield stress (f_t) to determine the strength parameters.

$$F_c = \frac{\sigma_1 - \sigma_3}{2} + \frac{\sigma_1 + \sigma_3 - 2\sigma_{rot}}{2} \; \frac{f_{cy}}{2\sigma_{rot} + f_{cy}} \qquad (2)$$

$$F_t = \sigma_1 - f_t \qquad (3)$$

Where σ_1 and σ_3 are the major and minor principal stresses and σ_{rot} is the intersection of the Mohr-Coulomb failure envelope and the isotropic axis. For a given maximum friction angle of the failure envelope (ϕ_{max}), σ_{rot} can be formulated as:

$$\sigma_{rot} = \frac{f_c}{2}\left(\frac{1}{\sin \varnothing_{max}} - 1\right) \qquad (4)$$

2.2.3 Strain Hardening and softening behavior of the Concrete model

To describe the behavior of concrete in compression, the stress-strain curve is divided into four parts [26]. As shown in Figure 2, the curve in Part I represents the behavior of hardened concrete till it reaches the peak compressive strength which is followed by the linear softening behavior until the failure compressive strength (Part II) and the ultimate compressive strength (Part III). After that, the last part is reduced and remains constant at the residual strength of the concrete (Part IV). Due to considering the time-dependent behavior, the material parameters are governed by the normalized parameters in both compression and tension stress-strain curves of the Concrete Model.

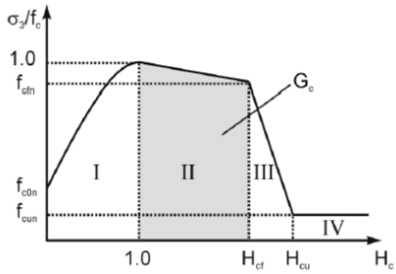


Fig. 2 Normalized stress-strain curve in compression

As mentioned above, the normalized values are employed for both horizontal and vertical axes in the compression stress-strain curve. The strain hardening/softening parameter ($H_c = \varepsilon_3^p / \varepsilon_{cp}^p$) normalized with the minor plastic strain (ε_3^p)and plastic peak strain in uniaxial compression (ε_{cp}^p) is used on the horizontal axis to plot against the ratio of minor principal stress (σ_3) by the compressive concrete strength (f_c) on the vertical axis as shown in the Fig. 2. Where H_{cf} is the strain hardening/softening parameter normalized with the failure plastic strain (ε_{cf}^p) which corresponds to the normalized compressive failure strength (f_{cfn}), H_{cu} is the strain hardening/softening parameter normalized with the ultimate plastic strain (ε_{cu}^p) which corresponds to the normalized compressive ultimate strength (f_{cun}). H_c = 1 corresponds with the full mobilized compressive strength, f_c = 1.

For the tension behavior of concrete, the stress-strain curve (Fig.3) is mainly described in two parts. Firstly, the linear elastic hardening behavior occurs in the concrete material under tension until it is reached to the peak tensile strength (f_t). Subsequently, it is reduced with the linear tension softening behavior until the ultimate tensile strength (f_{tu}). No further softening is taking place and remains constant when reached to the residual strength (f_{tun}).

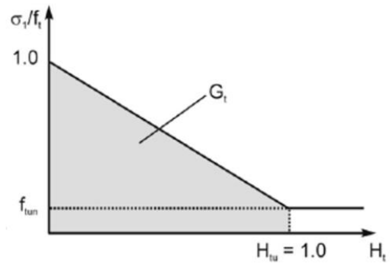


Fig. 3 Normalized stress-strain curve in tension

The strain hardening/softening parameter ($H_t = \varepsilon_1^p / \varepsilon_{tu}^p$) normalized with the major plastic strain (ε_1^p) and plastic ultimate strain in uniaxial tension (ε_{tu}^p) is used on the horizontal axis to plot against the ratio of major principal stress (σ_1) by the tensile concrete strength (f_t) on the vertical axis as shown in the Figure 3. Where H_{tu} is the strain softening parameter in tension normalized with the ultimate plastic strain (ε_{tu}^p) which corresponds to the normalized tensile ultimate strength (f_{tun}). H_{tu} = 1 corresponds with the full mobilized tensile strength, f_t = 1.

The shaded regions in both compression and tension curves characterize the area of fracture energy dissipates due to stress-strain response of the concrete material. The change of fracture energies with time describes the ductile behavior of the concrete during softening between the pre-peak and the post-peak stress conditions. Where the parameter G_c is the compressive fracture energy in compression curve and the parameter G_t is the tensile fracture energy in tension curve. The plastic failure strains in compression (ε_{cf}^p)and the ultimate peak strain in tension (ε_{tu}^p) can be derived from the fracture energy, G_c and G_t.

2.2.4 Creep and Shrinkage Behavior of the Concrete Model

The behavior of time-dependency in concrete or cement admixed material is governed by creep and shrinkage. When the concrete specimen is under sustained stress, the deformation gradually increases with time which produces the creep strain. Meanwhile, the shrinkage strain is independent of the stress state which occurs as the loss of volume with time. The time-dependent strains that are related to the aforesaid creep factor and shrinkage factor can be considered in the Concrete Model. The real behavior of concrete or cement treated soil is comprised of strain hardening/softening, creep, and shrinkage. The main advantage of the Concrete Model in PLAXIS is it can simulate the aforesaid features. Nevertheless, the time-dependency is switched off for this study since the primary objective of this paper is to propose the guidelines for application of Concrete Model in PLAXIS to cement-treated Bangkok clay which keeps the post-failure behavior. The material model parameters related to the time-independent behavior are mainly focused on this study.

2.3 Concrete model parameters in PLAXIS

The Concrete Model in PLAXIS 2D requires input 26 parameters in total which are related with strength and stiffness in compression, tension, and time-dependency. All the input parameters related to the Concrete Model in PLAXIS are listed in Table 1.

Table 1 Parameters of the Concrete model in PLAXIS

No.	Parameter	Unit	Description
1.	E_{28}	[kN/m²]	Young's modulus of cured concrete after 28 d
2.	ν	[-]	Poisson's ratio
3.	$f_{c,28}$	[kN/m²]	Uniaxial compressive strength of cured concrete after 28 d
4.	f_{c0n}	[-]	Normalized initially yield strength in compression
5.	f_{cfn}	[-]	Normalized failure strength in compression
6.	f_{cun}	[-]	Normalized residual strength in compression
7.	$G_{c,28}$	[kN/m]	Compressive fracture energy of cured concrete after 28 d
8.	ϕ_{max}	[°]	Maximum friction angle
9.	ψ	[°]	Dilatancy angle
10.	γ_{fc}	[-]	Safety factor for compressive strength
11.	$f_{t,28}$	[kN/m²]	Uniaxial tensile strength of cured concrete after 28 d
12.	f_{tun}	[-]	Normalized residual strength in tension
13.	$G_{t,28}$	[kN/m]	Tensile fracture energy of cured concrete after 28 d
14.	γ_{ft}	[-]	Safety factor for tensile strength
15.	t_{hydr}	[day]	Time for full hydration
16.	E_1/E_{28}	[-]	Ratio of Young's modulus after 1 d and 28 d
17.	$f_{c,1}/f_{c,28}$	[-]	Ratio of compressive yield strength after 1 d and 28 d
18.	ε_{cp}^p	[-]	Plastic peak strain in uniaxial compression
19.	$\varepsilon_{cp,1h}^p$	[-]	Plastic peak strain in uniaxial compression at 1h
20.	$\varepsilon_{cp,8h}^p$	[-]	Plastic peak strain in uniaxial compression at 8h
21.	$\varepsilon_{cp,24h}^p$	[-]	Plastic peak strain in uniaxial compression at 24h
22.	a	[-]	Increase of ε_{cp} with increase of confining pressure
23.	$\varepsilon_{\infty}^{shr}$	[-]	Final shrinkage strain
24.	t_{50}^{shr}	[-]	Time for 50% of shrinkage strains
25.	ϕ^{cr}	[°]	Ratio between creep and elastic strains

26.	t^{cr}_{50}	[-]	Time for 50% of creep strains

The total parameters of Concrete Model include the strength, stiffness and time-dependency related parameters which can exhibit the behavior of compression, tension, ductility, creep, and shrinkage. In PLAXIS finite element program, the drainage types are available to select as drained type and non-porous type. In this study, the time dependent strength, stiffness, creep, and shrinkage behavior are not investigated and disabled in the PLAXIS.

2.4 Experimental data collection

In the cement stabilization works, unconfined compressive strength (UCS) is a test method used to measure the strength of soil-cement with internal cohesion. The test is performed at a rapid strain rate with no confining pressure applied to the sample. The previous experimental work performing the unconfined compression test and undrained triaxial test on Bangkok clay admixed with various cement content, different water/cement ratio and initial clay-water content at different curing ages were collected in this study. According to the test results, it can be concluded that the cement content, clay-water-cement ratio, and curing period are the primary factors that influence the increase in strength and stiffness of cement-treated soil.

The experimental results of the Bangkok clay treated with Portland cement from previous studies were utilized to simulate the time-independent parameters of the Concrete Model. The Bangkok clay is the formation of the subsoil layers which are composed of the sedimentary deposits of the Chao Phraya River. According to previous extensive studies, the typical soil profile of Bangkok subsoils can be described as the alternating of very soft clay upper layers to stiff and hard clay layers at lower depth. The upper layers of soft to medium clay is generally known as the Bangkok Soft Clay layer which the approximate thickness is ranging from 12 m to 20 m of depth. The characteristics of the Bangkok clay prior cement treatment are 30 to 100 for liquid limit and 30 to 70 for the plastic index respectively. The natural water content is around 40 to 90% and the unit weight is 14 to 16 kN/m^3. The typical subsoil condition for this study was referred from campus of the Asian Institute of Technology (AIT), Bangkok reported by [18].

In this study, the series of unconfined compression tests and consolidated undrained triaxial test on Bangkok clay improved with Portland cement by [18] were utilized for Concrete Model application. High confining pressures ranging from 50 to 2000 kPa were applied during the undrained triaxial consolidated compression tests.

The unconfined compression tests were conducted to investigate the effects of several factors on the strength development and hardening of cement-treated Bangkok clay. These factors included the cement content, curing time, and the presence of a hardening effect. The tests covered a range of cement contents, from 5% to 40%, and the specimens were cured for a period ranging from 1 week to 6 months. The cement content (A_w) is defined as the ratio of the weight of the cement powder to the dry weight of untreated base clay which is expressed in percentage. The cement content for the soil-cement mixture can be obtained by calculating the total weight and the water content of the untreated clay. The experimental results used in this study were the soil-cement mixture with the cement content of 10%, 15% and 20%.

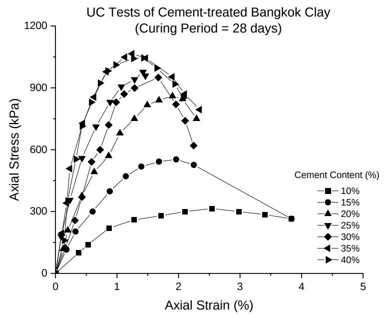


Fig. 4 Unconfined Compression (UC) Test Results of Cement-Treated Bangkok clay

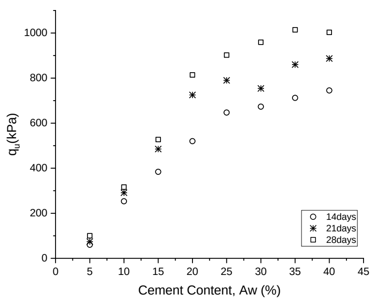


Fig. 5 Variation of Unconfined Compressive Strength with Cement Content

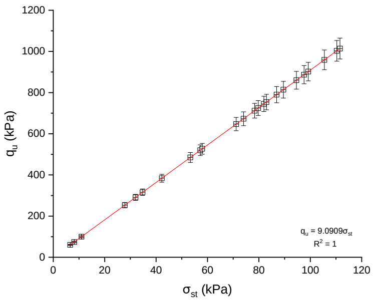


Fig. 6 Relationship between unconfined compression strength and splitting tensile strength by using $f_{t,28} = 0.11*f_c$

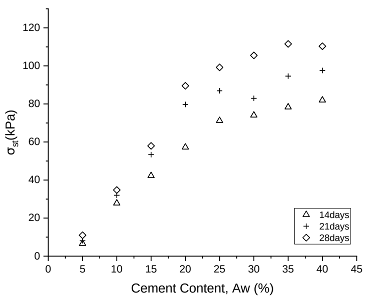


Fig. 7 Variation of Tensile Strength with Cement Content

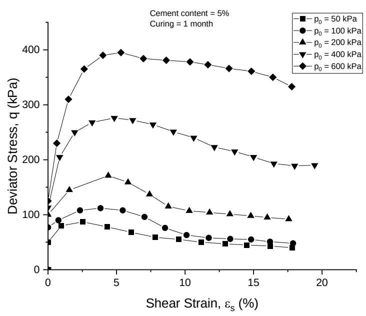


Fig. 8 Deviator stress-strain of treated Bangkok clay (Cement content = 5%)

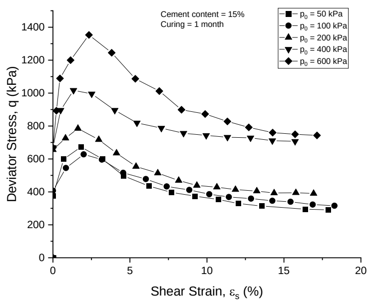


Fig. 9 Deviator stress-strain of treated Bangkok clay (Cement content = 15%)

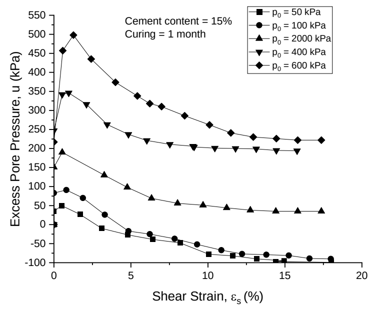


Fig. 10 Excess pore pressure-strain of treated Bangkok clay (Cement content = 15%)

The stress-strain response of the cement-treated Bangkok clay showed an increase in deviator stress at certain shear strain with increasing initial cell pressure. The pre-shear consolidated volumes were significantly impacted by the increase in p_0. Additionally, the relationship between deviator stress and shear strain was found to be dependent on the cement content, with the maximum deviator stress increasing as the cement content increased. The shear strain at maximum deviator stress decreased with increasing cement content. At 5% cement content, lower strain softening behavior was observed beyond the peak, while higher levels of softening were observed at 15% of cement content.

The time-independent compressive strength and stiffness soil parameters of cement-treated Bangkok clay used for the Concrete Model were calibrated in SoilTest facility in PLAXIS based on the above unconfined compression test results. For the tensile strength, it was taken from the direct correlation with the compressive strength as $f_{t,28} = 0.11*f_c$ according to [9], [10], [22], [24].

2.5 Calibration of the Concrete model parameters

The simulation results were compared to available measured data from previous experiments to adapt the analysis parameters. The time-independent strength and stiffness parameters of the Concrete Model were calibrated for cement treated Bangkok clay by employing the consolidated undrained triaxial compression test simulation in the SoilTest facility in PLAXIS. The SoilTest option enables the evaluation of material models and their parameters in both controlled soil lab test conditions and varying stress-strain scenarios. By comparing the model response with actual lab test data, the accuracy of approximation can be assessed between the real soil behavior and the model. However, it is important to acknowledge that calibrated material models are not reliable to be used in practical applications, where conditions differ from the lab. Since it may still result in discrepancies between the finite element model and reality. Nonetheless, utilizing the SoilTest facility can aid in comprehending the capabilities and constraints of the material model, as well as the impact of the model parameters. The comparison between experimental results and the SoilTest simulation results are presented in Figure 11 and 12.

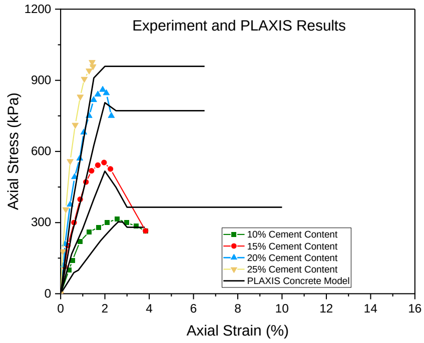


Fig. 11 Experimental and simulation results 1

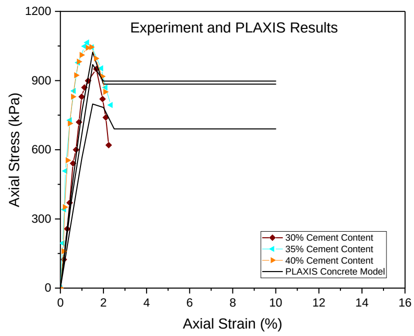


Fig. 12 Experimental and simulation results 2

2.6 Results and discussion

Figures 11 and 12 show the stress-strain curves for 10%,15%,20%,25%,30%,35% and 40% of cement content admixed with native Bangkok soft clay for both experimental and simulated by the Concrete Model. The highest unconfined compressive strength was obtained as the cement content increased which exhibits a brittle behavior after the maximum axial stress and then the strength gradually reduced. The hardening behavior is influenced primarily by the cement content and the curing times in the treated clay. The range of cement content between 10% to 20% was the most effective to be in hardening phase. The input material parameters for 20%, 30% and 40% of cement-treated Bangkok clay employed for the Concrete Model is presented in the below table. The simulation results, the Concrete Model can exhibit the softening part and residual part as the post-peak behavior. The utilized experimental tests were stopped at the softening part and the residual parts were not enough to compare with the simulation.

Table 2 Input parameters of the Concrete model in PLAXIS

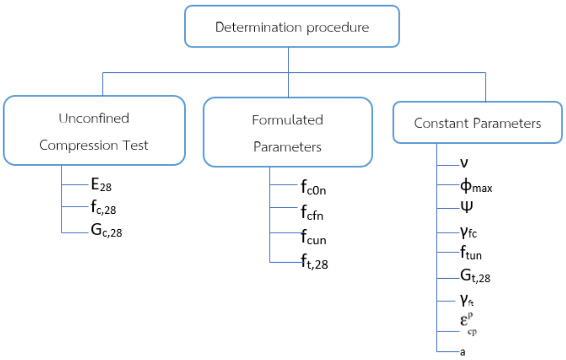
Parameter	Unit	Aw =20%	Aw =30%	Aw =40%
E_{28}	[kN/m^2]	45339	56852	73218
ν	[-]	0.25	0.25	0.25
$f_{c,28}$	[kN/m^2]	814	950	1045
f_{c0n}	[-]	0.1462	0.5695	0.1531
f_{cfn}	[-]	1.0393	1.0095	1.0000
f_{cun}	[-]	0.9214	0.6526	0.8144
$G_{c,28}$	[kN/m]	0.0021	0.00390	0.00333
ϕ_{max}	[^{o}]	30	30	30
ψ	[^{o}]	0	0	0
γ_{fc}	[-]	1	1	1
$f_{t,28}$	[kN/m^2]	89.54	104.5	114.95
f_{tun}	[-]	0	0	0
$G_{t,28}$	[kN/m]	0.005	0.005	0.005
γ_{ft}	[-]	1	1	1
t_{hydr}	[day]	28	28	28
ε^p_{cp}	[-]	-0.00246	-0.00246	-0.00246
a	[-]	0	0	0

There is a total of 26 parameters to input the Concrete Model including for time-independent and time-dependent properties. In this study, the time-dependent parameters were ignored, and the remaining 16 time-independent parameters were investigated for cement-treated Bangkok clay. First, the laboratory results from unconfined compression tests and consolidated triaxial compression tests of cement-treated Bangkok clay were collected and calibrated by calibration tool. Then, the experimental series which performed, and curves presented with all known excess pore pressure-strain, axial stress-strain were collected as a trial to derive the strength and stiffness parameters. To reassess those calculated strength and stiffness parameters in the Concrete Model, the SoilTest tool by PLAXIS was utilized. The SoilTest enables us to review and quickly determine the stiffness and strength parameters of the estimated soil models and compare them with calculated values from real experimental results. It can function as a virtual laboratory to conduct various laboratory tests under different test conditions. In this study, the laboratory test data obtained from previous literatures were compared with the stress-strain data obtained from Concrete Model parameters employment in

SoilTest to achieve the best fit between laboratory test data and the model results.

2.7 Determination approach for the Concrete model parameters of cement-treated Bangkok clay

The above parameters were approximated mainly based on the unconfined compression test results plus consolidated undrained triaxial test results and the step-by-step approach for this study was presented in Figure 13



. **Fig. 13** Schematic Diagram for the Determination Approach of Concrete Model Parameters

From the unconfined compression test results: the parameter $f_{c,28}$ can be determined from the peak unconfined compressive strength of axial stress-strain response of experimental results. The value of E_{28}, was approximated from the linear part of stress-strain curve in the elastic region. The compressive fracture energy, $G_{c,28}$ was calculated from the area between peak and failure stress-strain response.

The normalized compressive strength parameters such as f_{c0n}, f_{cun}, f_{cfn} were defined from the yield strength, failures strength and residual strength from the compressive stress-strain response by employing the formulae recommended in the PLAXIS manual. The residual strength values may have discrepancies since the employed experimental results were collected until the peak stage performed. For the tensile parameter, $f_{t,28,}$ the correlation between compressive strength and tensile strength was used to determine. However, the normalized residual strength, f_{tun} and tensile fracture energy, $G_{t,28}$ was assumed to be constant based on the correlated value since the tensile strength tests were not utilized in this study.

For the parameters of angle of internal friction, ϕ_{max} and dilatancy angle, Ψ, it can be computed from the triaxial compression tests. In this study, the values for those parameters, Poisson's ratio, and safety strength parameters were set to be constant which the set value is in the range of recommended values by pervious researchers regarding deep cement mixing and cement-treated soil studies. The input value of time-dependent plastic peak strain, ε^{p}_{cp}, was assumed to be constant at -0.2% beyond time 28 days.

In this study, the relevant variables needed to predict the stress-strain relationship of cement-treated Bangkok clay was briefly summarized. The "SoilTest" tool in PLAXIS to simulate the stress-strain behavior of the cement-treated clay using the Concrete Model. To verify the simulation results, experimental data from [18] on Bangkok clay treated with varying cement content was primarily selected. After calibration, the strength and stiffness parameters for the Bangkok clay treated with different cement content were adjusted for determining these parameters based on the calibration results. It is anticipated that this parameter determination procedure will also be partially applicable to clay treated with cement content for the future works.

The Concrete Model was originally developed for concrete and the plastic time-dependency during hardening, softening, creep and shrinkage with the change of fracture energies of cured concrete can be considered. For the concrete material of Concrete Model, there had recommended values for the input parameters for both time-dependent and time-independent strength and stiffness of concrete and the types of experimental laboratory tests were also suggested in the PLAXIS material model manual. In this study, the model parameters were collected through the previous performed results from literature and not directly derived from the laboratory tests. Therefore, to establish the appropriate set of Concrete Model parameters for the cement-treated Bangkok clay, it is required to perform the laboratory tests to derive the better accurate values which can be applied for the potential design considerations of soil improvement works by deep cement mixing. The experimental works to derive the parameters were proposed in the following table.

Table 3 Proposed Laboratory Tests for Cement-treated Clay

Parameter	Proposed Laboratory Tests
E_{28}	Uniaxial compression test Unconfined compression test
v	
$f_{c,28}$	
f_{c0n}	

f_{cfn}	
f_{cun}	
$G_{c,28}$	Uniaxial compression test Flexural test
ϕ_{max}	Triaxial tests
ψ	
$f_{t,28}$	Direct or indirect tensile test Direct correlation with the compressive strength
f_{tun}	Direct or indirect tensile test
$G_{t,28}$	Uniaxial tensile test Flexural test
ε^{p}_{cp}	Unconfined compression and tensile tests
a	Triaxial tests

3. Conclusions

This study has presented a brief introduction of the Concrete Model, an approach to determine the model parameters to predict the behavior of Bangkok clay improved with Portland cement by employing the Concrete Model in PLAXIS 2D. In this study, the results of unconfined compression test were utilized from previous experiment to compare with the simulation results of the Concrete Model in PLAXIS.

The study has verified that the Concrete Model is suitable for predicting the hardening stress-strain response of cement-treated clay. A method to determine the material properties necessary for utilizing the Concrete Model has been documented in literature and has been applied effectively to model concrete structures and deep cement mixing walls. Nevertheless, when simulating cement-treated soil, the present approach's parameters may need calibration to match the experimental data, particularly in the residual regions. Therefore, some material parameters require modification to better align with the test results, and certain parameters may need to be assigned constant values. Due to limited test data on cement-treated clay, the normalized stress values of tensile and tensile fracture energy, which govern the tension-softening response, are typically assumed. The Concrete model parameters utilized to analyze the compressive behavior of cement-treated soil were collected from literature data since there was a lack of comprehensive laboratory testing.

This study proposes a new approach for obtaining the material parameters necessary for the Concrete Model to accurately predict the behavior of cement-treated clay. The parameters are determined through the analysis of triaxial and unconfined compression test results.

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