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Predicting the Behaviour of Fibre Reinforced Cement Treated Clay

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Abstract
Treating soft clay with cement and fibre has become an effective ground improvement technique for transport infrastructure. Application of recycled fibres in deep soil mixing columns in soft soil sections of road and rail projects is being considered by designers and clients as an efficient technique. However, the combined effect of cement and fibre at failure requires further investigation. As the effective stresses increase to a sufficiently high stress, the effect of cementation is diminished due to the degradation of cementation bonds and the fibre exhibits failure due to either complete pull-out or breakage from the soil matrix. Thus, the failure envelope of the reinforced soil gradually merges with that of un-reinforced soil at higher stresses. In this paper, a constitutive model is proposed to simulate the behaviour of the cement treated-fibre reinforced soil based on the Critical State Soil Mechanic and the Modified Cam Clay model. In particular, the proposed model captures the beneficial effects of cementation and fibre reinforcement such as the improvement in strength and ductility while the cementation degradation and the failure mechanism of the fibre are also considered. In addition, a series of un-drained triaxial tests were conducted to verify the performance of the proposed model. This paper concludes that adding fibre into the cement treated soil clearly improves its residual strength, thus, a significant increase in ductility is observed and well simulated. In this study, by modifying the mean effective stress to include the cementation degradation and the fibre failure mechanism, the proposed model results in realistic prediction for the behaviour of soil treated with cement and fibre.

*Keywords:*cement treated fibre reinforced soils, constitutive modeling, cementation degradation, fibre failure mechanism

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1 Introduction

Stabilising soft soil with cement has become an effective ground improvement technique to strengthen the properties of the soft soil which involves mixing in-situ soil with cement to form soil-cement column. According to Porbaha (1998), the cement treated clay generally has higher strength, lower permeability and controlled deformation as compared to the un-treated soft soil. The properties of the cement treated clay are improved mainly due to the chemical interaction between cement and the soil particles to enhance the structure of the soil-cement matrix (Kamruzzaman et al., 2009). However, the cement treated soil becomes more brittle as compared to the un-treated soil due to the addition of cement. The brittle behaviour of cement treated soil is unfavourable as the strength suddenly drops to the residual strength (Lorenzo and Bergado, 2006).

In recent years, the use of fibre reinforcement to improve the strength and particularly the ductility of soft soil with and without cement treatment has been carried out by a number of researchers such as Michalowski and Cermák (2003)andTang et al. (2007). In particular, as reported by Michalowski and Cermák (2003) for fibre improved sand, the peak and residual strengths of both cohesive and cohesionless soil increase due to fibre reinforcement. While most of the previous studies focused on the improvement of fibre inclusion on sand and cement treated sand, only a few number of researchers such as Cai et al. (2006) and Fatahi et al. (2012)have focused on the fibre reinforced cement treated clay. Preliminary results suggested that the addition of fibre improves the overall performance of the cement treated clay, particularly the material ductility (Cai et al., 2006). Tang et al. (2007)explained that, the effect of fibre reinforcement is to increase the load transfer capacity from the soil-cement matrix to the fibre body, consequently the fibre connects the soil-cement clusters and provides the bridging effect preventing any further cracks within the sample. Thus, the large cracks which are normally observed in the failure of the cement treated clay are replaced by smaller cracks leading to an increase in material ductility. However, the behaviour of the cement treated clay reinforced with fibre under triaxial condition requires further investigation, particularly the failure mechanism of fibre and the effect of cementation degradation at high effective confining pressure. Thus, in this study, an undrained triaxial compression tests were conducted on cement treated clay and the results were reported for 5% cement and reinforced with 0% and 0.5% fibre to examine the effect of fibre reinforcement on the behaviour of cement treated clay.

Furthermore, this paper proposes a constitutive model to simulate the behaviour of cement treated clay reinforced with fibre. In the proposed model, the mean effective stress is modified to consider the combined effect of fibre and cement contribution to the shear strength, together with the effect of cementation degradation and the failure mechanism of the fibre. Moreover, an associated plastic flow rule and a general stress-strain relationship are proposed following the framework of Critical State Soil Mechanics and the basis of the Modified Cam Clay model. The proposed model is verified against the reported triaxial test results on cement treated fibre reinforced Kaolin clay. In this paper the cement treated fibre reinforced clay is referred to as the improved clay composite for reader convenience.

2 Effect of Cementation Degradation and Fibre Failures

Research shows that the shear strength of the cement treated clay increases as compared to the un-treated clay due to the effect of cementation and the formation of cementation bonds (Lorenzo and Bergado, 2006). According to Lorenzo and Bergado (2006), the treated soil can attain a higher yield stress as compared to the un-treated soil at the same void ratio in isotropic compression. However, as the confining pressures continue to increase beyond the initial yield stress, the void ratio reduces as the soil-cement clusters collapse and the cementation bonds begin to break. Furthermore, when the treated sample is deformed under shearing at high mean effective stress (or effective confining pressure) where plastic deformation occurs, the contribution of cementation to the shear strength diminishes due to the breaking of cementation bonds or the effect of cementation degradation (Kamruzzaman et al., 2009). At the post peak state, crushing of cementation bonds occurs resulting to a reduction in the shear strength which is due to the plastic shear strain as suggested by Suebsuk et al. (2010). When the shear strain becomes significantly large, the cementation bonds are completely removed; hence the behaviour of cement treated clay is similar to the un-treated clay. At this stage, the stress state of the cement treated clay lies on the Critical State Line (CSL) of the reconstituted soil-cement mixture. Nguyen et al. (2014) proposed a constitutive model to capture the effect of cementation and its degradation due to increasing effective confining pressures.

For the improved soil composite, Tang et al. (2007) explained that the frictional and interlocking forces between the fibre body and the surrounding tightly packed soil-cement clusters increase as the fibre is mobilised during loading. When the fibre is fully mobilised, the applied load is transferred effectively to the fibre body, enhancing the connection between fibre and the soil-cement matrix. Furthermore, the failure modes of the fibre reinforced soil are classified as pull-out or breakage which are characterised by the critical confining pressure (Zornberg, 2002). Below this critical confining pressure, the failure mechanism is assumed to be pull-out as the fibre is not fully mobilised. However, when the sample is loaded beyond the critical confining pressure, the fibre tends to become plastic and possible breakage may occur as the frictional and the interlocking forces increase significantly. Hence, the effectiveness of fibre reinforcement reduces due to fibre failure. Overall, the combined effect of fibre and cement contribution to the shear strength of the improved soil composite diminishes with increase in confining pressure.

3 Development of Constitutive Model

In this model, the effect of cementation and its degradation to the shear strength were assumed to be dependant on the level of mean effective stress. When the improved soil composite is sheared under the mean effective yield stress (p'_0) lower than the initial mean effective yield stress ($p'_{0,i}$), only elastic deformation occurs, so the contribution of cementation is most effective in this range. However, when $p'_0 > p'_{0,i}$, plastic deformation occurs causing the cementation bonds to break. Hence, as the mean effective yield stress continues to increase, the effect of cementation is gradually diminished. Furthermore, the breaking of cementation bonds is also due to the plastic deviatoric strain caused by shear deformation. Thus, in the proposed model, the mean effective stress was modified to consider the effect of cementation and its degradation due to the combined effect of volumetric and shear deformation. On the other hand, the contribution of fibre to the shear strength was formulated depending on the level of the deviatoric stress since the frictional and interlocking forces between fibre and the surrounding soil-cement clusters are mobilised when subjected to shearing. As mentioned earlier, the failure of the fibreis governed by either pull-out or breakage. However, for simplicity, the proposed model assumes that the effect of fibre is diminished when the fibre is gradually pull-out from the soil-cement clusters at sufficiently high deviatoric stresses. The effect of fibre reinforcement and its failure mechanism is formulated as an addition to the mean effective stress. Hence, to consider the combined effect of cementation and its degradation together with the effect of fibre and its failure, the modified mean effective stress (p'^*) takes the following form:

$$p'^* = p' + \frac{\left(\frac{C}{M}\right)\left[1 + \left(\frac{p'_0 - p'_{0,i}}{\beta}\right)\right] exp^{-\left(\frac{p'_0 - p'_{0,i}}{\beta}\right)} + \left(\frac{z}{M}\right) q exp^{-nq}}{1 + m\varepsilon_q^p exp^{(m\varepsilon_q^p - \mu)}} \tag{1}$$

where, p', q and ε_q^p are the mean effective stress, deviatoric stress and plastic deviatoric strain, respectively, which are the stress and strain quantities used in the Modified Cam Clay (MCC) model. $M$is the slope of the Critical State Line of the reconstituted soil composite. Moreover, C and z present the contribution of cementation and fibre to the shear strength of the improved soil composite, respectively. The parameters β and n affect the degradation rate of cementation and fibre failure, respectively. Furthermore, m and μ are the fitting parameters reflecting the degradation rate of cementation due to shear deformation. It should be noted that, when C and z are set to be zero, the combined effect of cementation and fibre is diminished and the modified mean effective stress (p'^{*}) returns to p' in MCC model. Equation (1) was formulated in a way that when p'_0 or ε_q^p increase to sufficiently high values, the effect of cementation is completely destroyed. Moreover, as deviatoric stress becomes very high, the fibre failure governed by pull-out occurs diminishing the effect of fibre.

When the stress state is within the yield surface, only elastic deformation occurs. To simulate the behaviour of the improved soil composite, the proposed model adopts Hooke's law as used by many researchers such as Suebsuk et al. (2010)for cement treated clay. The elastic volumetric (d_v^e) and deviatoric strain increments (d_ε^e)are simulated using the following equations:

$$d_v^e = \left(\frac{\kappa}{1+e}\right)\left(\frac{dp'^{*}}{p'^{*}}\right) \tag{2}$$

$$d_\varepsilon^e = \left[\frac{2\kappa(1+\nu)}{9(1-2\nu)(1+e)}\right]\left(\frac{dq}{p'^{*}}\right) \tag{3}$$

where, κ is the swelling index of the isotropic compression line,e is the void ratio of the improved soil composite and ν is the Poisson's ratio.

Following the basis of MCC model, the proposed model assumes that the improved soil composite is an elastic and virgin yielding material. The proposed yield surface (f)has elliptical shape and the equation is formulated as follows:

$$f = q^2 - p'^{*2}M^2\left(p^{*\prime}{}_0 - p'^{*}\right) = 0 \tag{4}$$

where, $p^{*\prime}{}_0$ represents the size of the yield surface where it meets with the horizontal axis in $p' - q$ plane. Furthermore, when the stress state is on the yield surface and with $dp^{*\prime}{}_0 > 0$, virgin yielding occurs resulting to plastic deformation. For the improved soil composite, an associated plastic flow rule is developed, similar to the MCC model. In other words, the yield surface is identical to the plastic potential surface (i.e. $f = g$). Hence, the proposed plastic flow rule is formulated to consider the effect of cement and fibre as follows:

$$\frac{d_v^p}{d_\varepsilon^p} = \frac{\left(p'^{*2}M^2 - q^2\right)}{2qp'^{*}} \tag{5}$$

where, d_v^p and d_ε^p are the plastic volumetric and deviatoric strain increments, respectively.

When virgin yielding occurs, the yield surface expands in size to accommodate the change in stress state. According to Wood (1990), the expansion in the yield surface is caused by the plastic volumetric and deviatoric strains. However, to follow the basis of MCC model, the proposed model assumes that only plastic volumetric strain causes the yield surface to expand. Hence, with the proposed associated flow rule and adopting the normality rule (i.e. $d_v^p/d_\varepsilon^p = -dq/dp'$), the plastic volumetric and deviatoric strain increments can take the following form:

$$d_v^p = \left(\frac{\lambda-\kappa}{1+e}\right)\left[\frac{dp'^*}{p'^*}+\left(\frac{-qdp'^*+p'^*dq}{p'^{*2}}\right)\left(\frac{2qp'^*}{q^2+p'^{*2}M^2}\right)\right] \tag{6}$$

$$d_\varepsilon^p = \left(\frac{\lambda-\kappa}{1+e}\right)\left[\frac{dp'^*}{p'^*}+\left(\frac{-qdp'^*+p'^*dq}{p'^{*2}}\right)\left(\frac{2qp'^*}{q^2+p'^{*2}M^2}\right)\right]\left(\frac{2qp'^*}{p'^{*2}M^2-q^2}\right) \tag{7}$$

Thus, at this stage, the formulation of the proposed model for the hardening behaviour is complete. The general stress-strain relationship to describe the total volumetric $(d_v)$and deviatoric (d_ε) strain increments can be derived by combining Eq. (2) to Eq. (6) and Eq. (3) to Eq. (7), respectively, as follows:

$$d_v = \left(\frac{\kappa}{1+e}\right)\left(\frac{dp'^*}{p'^*}\right)+\left[\frac{dp'^*}{p'^*}+\left(\frac{-qdp'^*+p'^*dq}{p'^{*2}}\right)\left(\frac{2qp'^*}{q^2+p'^{*2}M^2}\right)\right] \tag{8}$$

$$d_\varepsilon = \left[\frac{2\kappa(1+\nu)}{9(1-2\nu)(1+e)}\right]\left(\frac{dq}{p'^*}\right)+\left(\frac{\lambda-\kappa}{1+e}\right)\left[\frac{dp'^*}{p'^*}+\left(\frac{-qdp'^*+p'^*dq}{p'^{*2}}\right)\left(\frac{2qp'^*}{q^2+p'^{*2}M^2}\right)\right]\left(\frac{2qp'^*}{p'^{*2}M^2-q^2}\right) \tag{9}$$

It can be noted that, when there is no effect of cement and contribution from fibre (i.e. C and z = 0), the proposed model returns to the MCC model. Furthermore, when the improved soil composite has reached the peak strength state, softening process occurs due to the breaking of cementation bonds which results to a reduction in the shear strength. However, the effect of fibre is fully mobilised at the post-peak state, so the fibre enhances the connection between the soil-cement clusters and the fibre. As the deviatoric strain increases, the fibre is gradually pulled-out from the soil matrix. Thus, in this model, to simulate the softening process including the effect of cementation degradation and fibre failure, the stress state of the improved soil composite was assumed to stay on the proposed failure line $(q = Mp'^*)$. Moreover, as plastic deviatoric strain (ε_q^p) increases, the combined effect of cementation and fibre reduces directing the stress state toward the Critical State Line $(q = Mp')$. When $\varepsilon_q^p \to \infty, p'^* \to p'$, the softening process can be simulated using the proposed failure line as follows:

$$q = Mp' + \frac{C\left[1+\left(\frac{p'_0-p'_{0,i}}{\beta}\right)\right]exp^{-\left(\frac{p'_0-p'_{0,i}}{\beta}\right)}+zqexp^{-nq}}{1+mexp^{(m\varepsilon_q^p-\mu)}} \tag{10}$$

In addition, the detailed development of the proposed model can be found in Nguyen et al. (2016) with non-associated plastic potential function.

4 Model Verification and Discussion

A series of undrained triaxial testswere conducted on 5% cement treated Kaolin clay reinforced with 0% and 0.5% fibre content at different mean effective yield stresses (i.e. p'_0 = 200, 400 and 800 kPa). Some of the properties of the Kaolin clay are summarised in Table 1. The parameters of the soil such as M, λ, κ, e and ν can be measured by conducting a conventional isotropic compression test. Moreover, parameter $p'_{0,i}$ refers to the initial yield stress of the cement treated clay in isotropic consolidation test. The proposed model consists of parameters related directly to the effect of cementationsuch as C and β which can only be determined accurately by performing a set of triaxial tests on cement treated Kaolin clay only. Once those parameters are estimated, further parameters related to the effect of fibre can be determined by fitting the results from the triaxial test conducted on the cement treated fibre reinforced clay, particularly at the post peak state. The experimental results are displayed in Figures 1 and 2 in terms of undrained stress path in $p' - q$ plane and the stress-strain relationship in $\varepsilon_q - q$ plane, respectively.

Kaolin Clay	*LL*	*PL*	*PI*	G_s	*Colour*	*USCS*
Measured in laboratory tests	48%	29%	19%	2.66	White	CL
	λ	κ	e	υ	M	$p'_{0,i}$ (kPa)
Measured in laboratory tests	0.346	0.048	2.15	0.25	1.09	185
	C (kPa)	β (kPa)	m	μ	z (kPa)	n
Estimated	92.5	2487	95	3.2	120	0.0025

Table 1: Properties of Kaolin clay and model parameters

The proposed model was evaluated by comparing its predictions with the experimental results of the improved Kaolin clay composite with 0.5% fibre content as shown in Figures 1 and 2. The cement treated clay without fibre reinforcement showed strain hardening brittle behaviour as the shear strength increased to the peak and then suddenly dropped to a residual strength state with increasing deviatoric strain (ε_q). Moreover, the peak shear strength (q_{peak}) of the cement treated clay was above the Critical State Line (CSL) indicating the contribution of cementation to the shear strength, then it reached the residual strength at the CSL showing the crushing of cementation bonds. In contrast, the improved clay composite with 0.5% fibre showed strain hardening ductile behaviour as the shear strength gradually reduced at the post-peak state with increase in ε_q. Furthermore, as shown in Figure 1, the residual strength state of the improved clay composite was observed above the CSL indicating the bridging effect provided by the fibre. While the residual shear strength was influenced by the effect of fibre, q_{peak} of the improved clay composite was governed mainly by the effect of cementation as the contribution of the fibre to the peak shear strength was minimal as shown in Figure 2. In fact, at high mean effective yield stress (i.e. p'_0 = 800 kPa), q_{peak} values of the cement treated Kaolin with and without fibre inclusion were almost identical and the behaviour of the improved clay composite showed brittle failure as the sample softened with increasing strain. This is due to the effect of cementation degradation caused by high mean effective yield stress and large accumulation of plastic shear strain within the sample. Moreover, the fibre may be pulled-out due to shear deformations.

The proposed model has simulated the behaviour of the 5% cement treated Kaolin clay with 0.5% fibre inclusion very well, as shown in Figures 1 and 2. The peak shear strength was captured by accurate estimation of the effect of cementation (C) and the effect of fibre (z). Furthermore, the transition from the peak to the residual strength state was smoothly simulated by considering the effect of shear deformations in the parameters $m$and μ, together with β and n affecting the degradation rate of cement and fibre. Also, the softening process of the improved clay composite has been simulated very well adopting Eq. (10). Moreover, to simulate the cement treated clay with 0% fibre content, the effect of fibre (z) and its associated degradation (n) are diminished (i.e. z = 0 and n = 0).

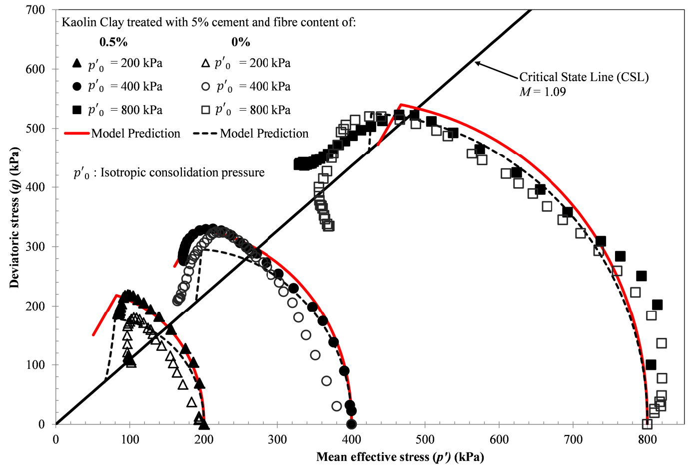

Figure 1: Undrained stress paths of 5% cement treated Kaolin clay reinforced with 0% and 0.5% fibre

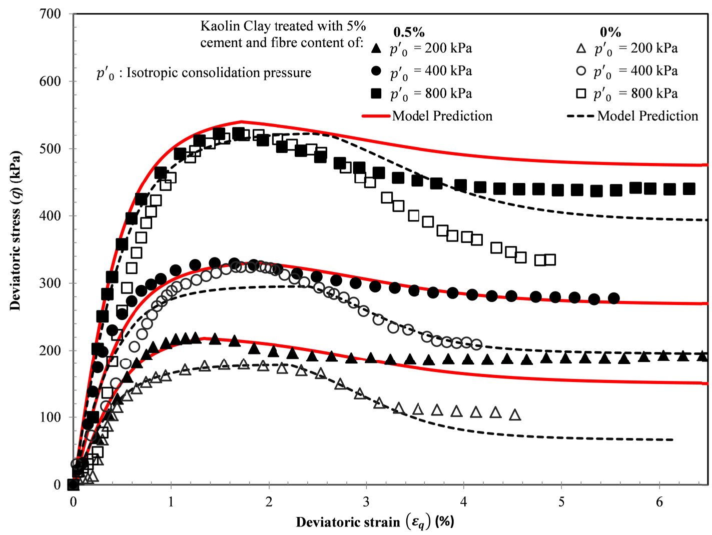

Figure 2: Stress-strain relationship of 5% cement treated Kaolin clay reinforced with 0% and 0.5% fibre

Due to limitation of number of pages, further experimental results (e.g. different cement and fibre contents) and model verification exercises can be found in Nguyen et al. (2016). For further development of the proposed model, the viscoplastic deformation on the long term time dependent behaviour of the improved soil composite should be included which has been studied for soft soil by a number of researchers such as Azari et al. (2015) and Le et al. (2015). Moreover, the analytical solution proposed by Ho et al. (2015) can be incorporated into the proposed model to predict the deformation of the stabilized soil in unsaturated condition.

5 Conclusions

The peak shear strength of the improved clay composite depends on the effect of cementation while the bridging effect provided by the fibre facilitates to increase the residual strength. However, high mean effective yield stress and large shear strain cause significant breaking of cementation bonds and fibre failure, consequently reducing the effectiveness of both cement and fibre. By considering the effect of cementation degradation and fibre failure mechanism, the proposed constitutive model has captured some important features of the improved clay composite behaviour, particularly the peak and the residual shear strength values. Thus, the proposed model is recommended to practicing engineers to simulate the behaviour of the cement treated clay reinforced with fibre.

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