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EFFECT OF THE CURING TIME ON THE NUMERICAL MODELLING OF THE BEHAVIOUR OF A CHEMICALLY STABILISED SOFT SOIL

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Abstract. The ability of the Modified Cam Clay (MCC) model combined with the Von Mises (VM) model, considering the effect of curing time on the enhancement of the mechanical properties of a chemically stabilised soft soil is examined. The evolution of the strength and stiffness over time is based on the results of undrained compressive strength (UCS) tests carried out for different curing times (from 28 days to 360 days). Initially, the MCC/VM models associated with the effect of curing time are validated by CIU triaxial tests, for curing times of 28 and 90 days. Finally, the behaviour of an embankment built on a soft soil reinforced with deep mixing columns is predicted based on the previously validated models. The results show that the increase of curing time of the DMCs slightly decreases the settlement obtained with a curing time of 28 days.

1 INTRODUCTION

Over the last years, various embankments have been built on soft soils. In general, these types of soils show high compressibility, low undrained shear strength and reduced permeability. One way to solve these problems consists of installing rigid vertical inclusions in the soil foundation, such as: concrete piles, stone columns and deep soil mixing columns (DMCs), i.e., of chemically stabilised soil columns.

Several experimental studies have shown that, due to pozzolanic reactions, the strength and stiffness of the stabilised soils increases over time [1-3]. However, the current design of stabilised soils uses the mechanical properties evaluated for 28 days of curing as a reference [4, 5]. Considering the lack of the numerical studies related to the enhancement of the mechanical properties of stabilised soils over time, it is very pertinent to study the impact of this effect on numerical predictions.

2 SCOPE OF THE WORK

Initially, the performance of the Modified Cam Clay (MCC) model associated with the Von Mises (VM) model and considering the effect of the curing time is validated using the results of triaxial CIU (isotropic consolidation followed by an undrained shear phase) tests for two curing times, 28 and 90 days [1]. Finally, the effect of the curing time on the settlement and the stress concentration ratio of an embankment built on a soft soil reinforced with DMCs is analysed.

A 2-D finite element code with several constitutive models was used, upgraded at the University of Coimbra and capable of carrying out elastoplastic analyses with coupled consolidation and creep.

3 CONSTITUTIVE MODEL

The behaviour of the stabilised soil is simulated by two coupled constitutive models (Figure 1), MCC/VM, which show two yield functions that may be activated either independently or simultaneously. Both models (MCC and VM) assume a linear elastic behaviour inside the yield surface and consider an associated plastic flow rule.

The yield function of the MCC model is represented by an ellipse-shaped surface oriented in line with the p' axis, described by [6, 7]:

$$F = (\lambda - \kappa).\ln\left[p'\left(1 + \frac{(q/p')^2}{M^2}\right)\right] - \underbrace{\left[\underbrace{e_{\lambda o} - \underbrace{(e + \kappa.\ln p')}_{e_\kappa}}_{h(e_\kappa)} + \underbrace{(\lambda - \kappa)\times\ln\frac{p'_{c(t_c)}}{p'_{c(t_c=28d)}}}_{\Delta h(t_c)}\right]}_{h(e_k,\, t_c)} \tag{1}$$

where M is the slope of the critical state line (CSL), λ and κ are, respectively, the slope of the virgin consolidation line and the slope of the overconsolidation line in the plot e-lnp' and $e_{\lambda o}$ is the void ratio for p' equal to 1 (Figure 1a). The size of the yield function changes with the hardening rule $h(e_k, t_c)$, related to the isotropic preconsolidation pressure, p'_c (Figure 1b), which depends on the void ratio (e_k) and the curing time (t_c). The t_c promotes the change of $h(e_k, t_c)$ which induces an increase in the apparent p'_c and consequently $e_{\lambda o}$ (Figure 1). The VM model is described by [6, 8]:

$$G = q - \underbrace{q_c}_{h\left(\gamma^p,\, \varepsilon_v^p,\, t_c\right)} \tag{2}$$

where $h\left(\gamma^p, \varepsilon_v^p, t_c\right)$ is the hardening rule, represented by the parameter q_c. The hardening rule is evaluated considering that the trace of the yield surface on the q-γ plane is a hyperbola [9, 10]:

$$q_c = \frac{\gamma\, p'_c}{a + b\gamma} R_f \tag{3}$$

where a and b are normalized hyperbolic parameters, and R_f ($q_{failure}/q_{ult}$) is the failure ratio [11].

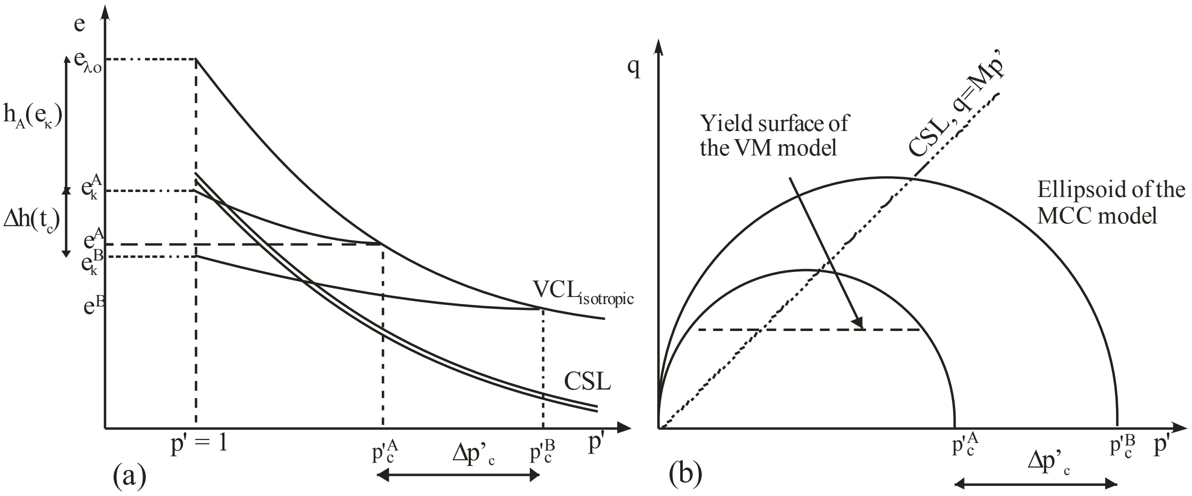

Figure 1: Effect of creep and curing time on the MCC model: a) hardening rule (e-p' plane); b) yield surface (p'-q plane).

4 EFFECT OF CURING TIME ON STABILISED SOIL

Figure 2 depicts the evolution of the unconfined compressive strength ratio ($q_u/q_{u\text{-}28d}$) against curing time (from 28 to 360 days). The results show that $q_u/q_{u\text{-}28d}$ increases faster for shorter curing times, tending to reach a constant value for higher t_c. Thus, for a curing time higher than 360 days, it is assumed that there is no increase of the cementation bonds, i.e., q_u is constant and equal to the value obtained for 360 days.

Considering that the power function presented in Figure 2 reflects the increase of the cementation bonds on the mechanical behaviour, a similar function is used to predict the evolution of the p'_c over t_c:

$$p'_{c(t_c)} = p'_{c(28d)} \times \left[0.4568 \times t_c^{\,0.2438}\right] \qquad (t_c \leq 360\ \text{days}) \tag{4}$$

The prediction of Young's modulus (E') over t_c, is based on equation (4), a reduction factor (F_{red} =0.4) is required to match the experimental results, taking the form of:

$$E'_{(t_c)} = E'_{(28d)} \times \left[E'_{(28d)} \times \left(0.4568 \times t_c^{\,0.2438}\right) - E'_{(28d)}\right] x\, \underbrace{0.4}_{F_{red}} \quad (t_c \leq 360\ \text{days}) \tag{5}$$

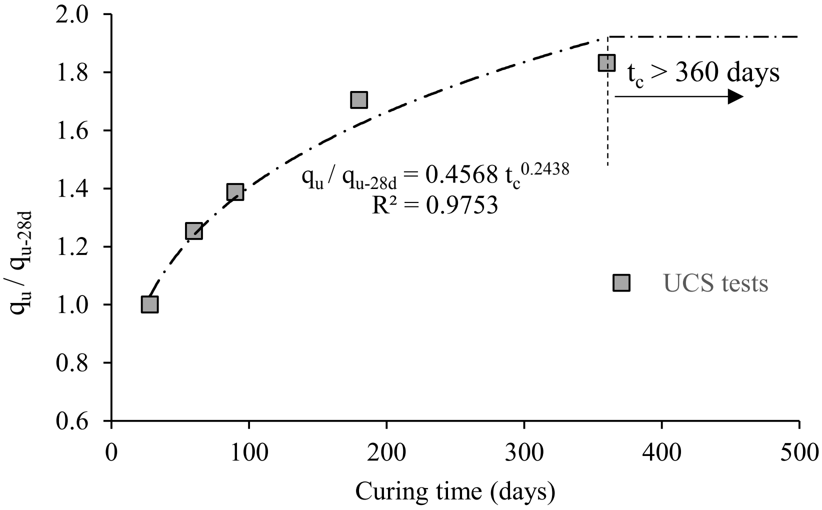

Figure 2: Effect of curing time on the unconfined compressive strength ratio [1].

Equations (4) and (5) are included in the finite element method (FEM) code, in order to take into account the effect of the curing time on the stiffness (E') and the size of the yield surface of the MCC model (p'_c).

5 NUMERICAL PREDICTION OF THE LABORATORY TESTS

Results of triaxial CIU tests were used to validate the CCM/VM model associated with the t_c effect. The numerical predictions were carried out with only 1 FE element (eight-noded isoparametric quadrilateral) and 8 nodes, making the evaluation of the displacement at eight nodes and the excess pore pressure at the four corner nodes possible. Table 1 shows the parameters for the MCC/VM model used in the numerical analyses.

Table 1: Parameters of the soft soil and the stabilised soil (i.e. DMCs) used in the numerical analyses [1].

Soil type		Stabilised soil/DMCs		
Curing time	t_c (days)	28	90	≥ 360
Elastic parameters	E' (MPa)	$164.7^{(*)}$	$189.0^{(**)}$	$225.2^{(**)}$
	ν	0.3	0.3	0.3
MCC model	$e_{\lambda 0}$	5.070	$5.204^{(\#)}$	$5.349^{(\#)}$
	e_0	(*)	(*)	(*)
	λ	0.435	0.435	0.435
	κ	0.0074	0.0074	0.0074
	M	1.50	1.50	1.50
VM model	a	0.0013	0.0013	0.0013
	b	1.683	1.683	1.683
	R_f	1.0	1.0	1.0

(*) Depends on the stress level;. (**) Evaluated from equation (5); (#) Evaluated from equations (1), (4).

Figure 3 compares the numerical predictions with the experimental results of the CIU triaxial tests carried out with samples of the stabilised soil, isotropically consolidated with a confining pressure (p'$_0$) of 50 kPa, for the curing times of 28 and 90 days. The results obtained show that the numerical models used are able to replicate the significant increase in the strength and the slight increase in the stiffness over curing time, due to the pozzolanic reactions which promote the increase of the cementation bonds. In fact, the stress-strain behaviour (Figure 3) obtained numerically matches the experimental results very well until the peak strength; however, after that, the MCC/VM model does not simulate the softening observed in the laboratory tests.

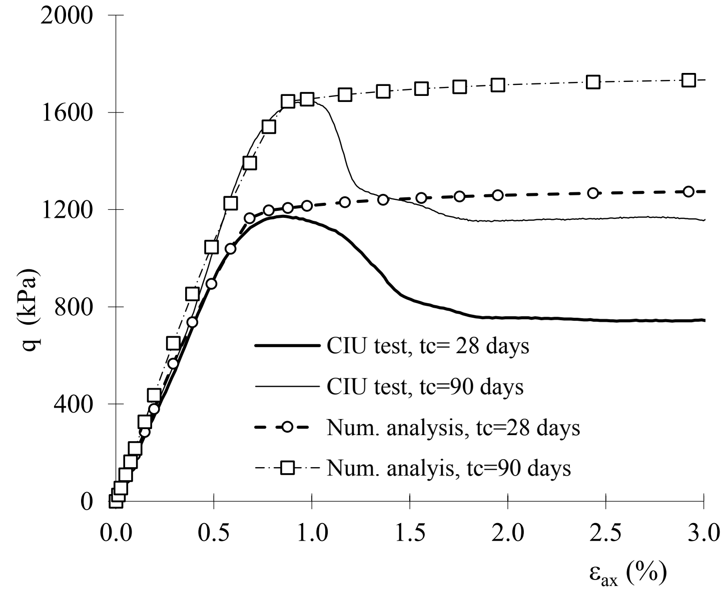

Figure 3: CIU tests with stabilised soil for a curing times of 28 and 90 days.

5 NUMERICAL PREDICTION OF THE BEHAVIOUR OF AN EMBANKMENT

5.1 Materials

The previously tested models are used to study the behaviour of a large-scale embankment built on soft soils reinforced with Deep Mixing Columns (DMCs), simulated by an axisymmetric cylindrical unit cell (Figure 4). The soil foundation is composed by 7.5 metres of soft soil placed under a 0.5 metre thick layer of sand. The water table is on the top of the layer of sand. The construction of the embankment consists of 4 sub-layers, each one with a thickness of 1.0 metre applied with a time delay of 5 days. The construction of the embankment started after a curing time for the DMCs of 28 days, in order to have the strength required in current design.

The finite element (FE) mesh used in the axisymmetric analysis consists of 130 eight-noded isoparametric quadrilateral elements and 355 nodal points. An FE with twenty nodal degrees of freedom was used below the water table, making it possible to simulate the consolidation phenomenon. In terms of boundary conditions of the FE mesh, the bottom boundary was restrained from moving in both directions, both lateral vertical sides were restrained from moving in the horizontal direction, the top boundary of the soil foundation is permeable, while the lateral and the bottom boundaries are impermeable.

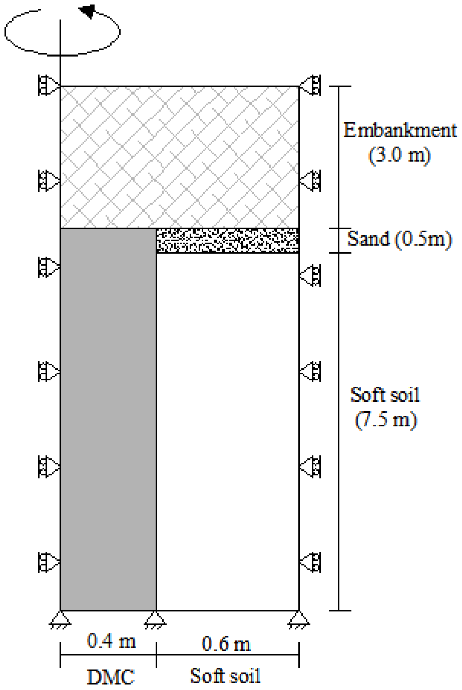

Figure 4: Embankment analysis. FEM mesh used.

The embankment material ($\gamma = 22$ kN/m^3) is simulated by an elastic law (E' varies between 15/10/5/1 MPa from the bottom to the top layer; ν'=0.3) associated with the Mohr-Coulomb criterion (c'= 10 kPa; ϕ'= 35º). The behaviour of the sand layer is replicated by a linear elastic law with the parameters: E'=2.0 MPa, ν'=0.3, γ = 15kN/m^3 and k= 10^{-4} m/s. The MCC/VM model is used to predict the behaviour of DMCs; the following parameters, other than those shown in Table 1, are considered: $K_0 = 0.8$ [12], γ = 16 kN/m^3, k= 3x10^{-10} m/s and k_h/k_v= 1.0. The soft soil is simulated by the MCC model with the parameters: $\lambda = 0.204$, $\kappa = 0.03$, M = 1.5, $e_{\lambda 0}$= 2.315, $K_0 = 0.4$, γ = 15 kN/m^3, k= 10^{-9} m/s and k_h/k_v= 3; Young's modulus of the soft soil is calculated by [13]:

$$E' = \frac{3(1+e_0)(1-2\upsilon')}{\kappa} p'_0 \tag{6}$$

where e_0 and p'_0 are the initial void ratio and volumetric effective stress respectively, ν' is the Poisson ratio and κ is the swell-recompression index. The coefficients of the permeability vary with the void ratio according to[14]:

$$k = k_0 x 10^{\frac{e - e_0}{C_k}} \tag{7}$$

where k_0 is the coefficient of permeability corresponding to e_0 and C_k is equal to $e_0/2$ [15].

5.2 Results and discussion

Four cases are modelled in this work. Case A analyses the behaviour of the embankment on the soft soil without DMCs. Cases B, C and D simulate the reinforcement of the soil foundation with DMCs, considering the properties of the DMCs evaluated for 28 days (Case B), 90 days (case C) and considering the enhancement of the their properties with the curing time (case D).

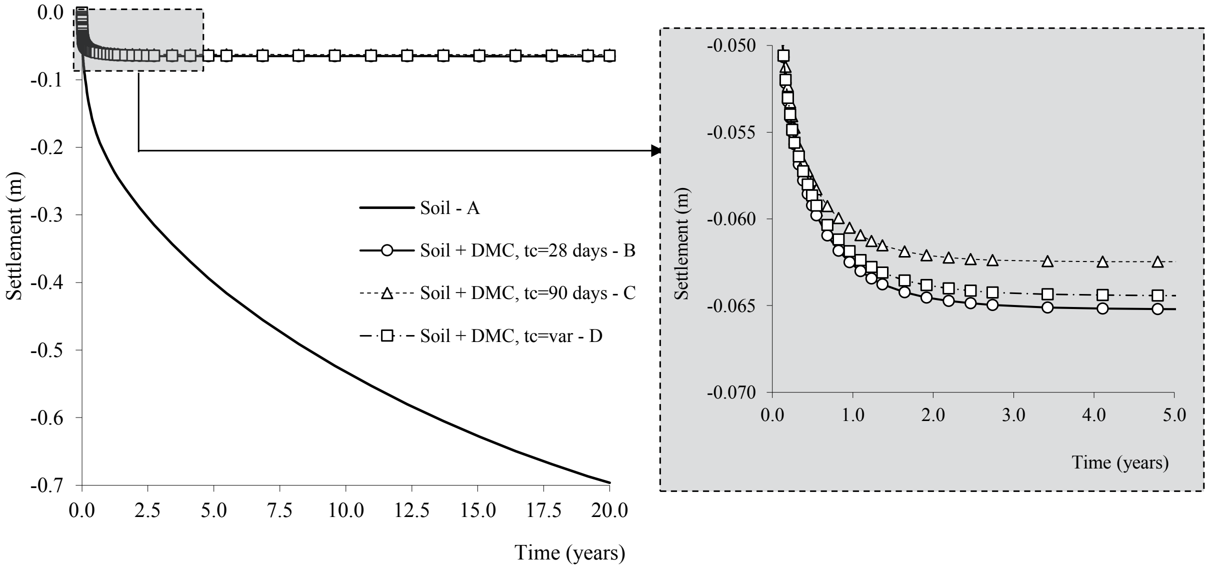

Figure 5: Embankment built on soft soils reinforced with DMCs. Evolution of settlement over time.

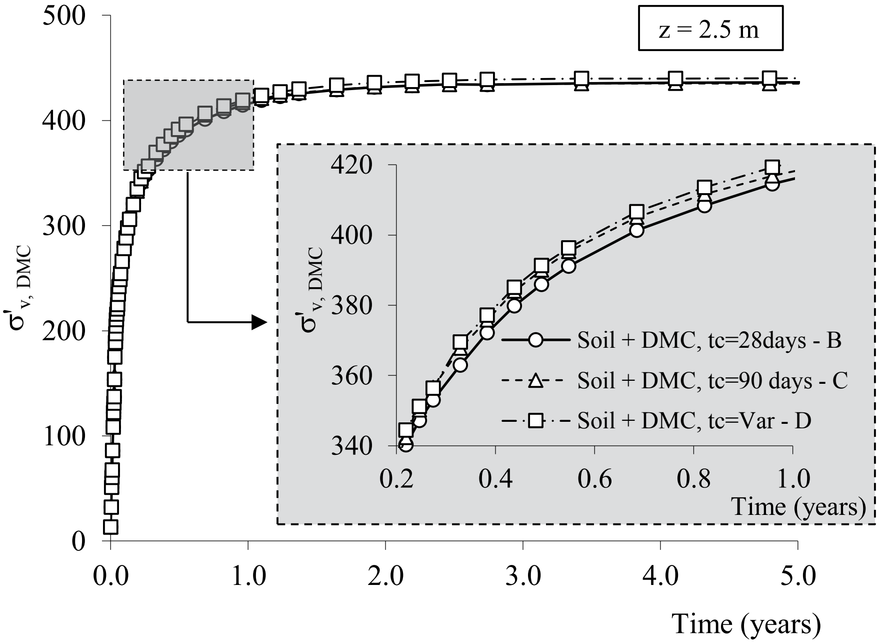

Figure 6: Embankment built on soft soils reinforced with DMCs. Evolution over time of the effective vertical stress on the DMCs.

Figure 5 shows the evolution of the settlement at the top of the soil foundation for the vertical axis of the unit cell over time. Firstly, it should be emphasised that the reinforcement of the soft soil with DMCs decreases the settlement of the embankment significantly, inducing, for a time of 20 years, a reduction higher than 10 times. Comparison of cases B, C, and D shows that the effect of the curing time has a low impact on the numerically predicted settlement. Indeed, the consideration of the variation of the mechanical properties with t_c (case D) decreases the settlement by about 1% in relation to case B (t_c=28 days), and increases the settlement by about 3% in relation to case C (t_c = 90 days). The high consolidation rate induced by the use of DMCs [4] results in the major part of the settlement occurring in a short period of time (after the placement of the embankment layers), therefore the mechanical properties of the DMCs are similar in cases B and D, which justifies the small differences obtained in both cases.

Figure 6 depicts the evolution over time of the effective vertical stress on the DMCs ($\sigma'_{v,DMC}$) for a depth of 2.5 metres. The results show a slight increase in the $\sigma'_{v,DMC}$ for higher curing times, that is from case B to C and from case C to D. Indeed, the increases of the stiffness, from cases B to D, promote the transference of stresses from the soil to the DMCs as a consequence of the “arching effect” [4].

6 CONCLUSIONS

This work studies the effect of curing time on the mechanical behaviour of a chemically stabilised soft soil. The relationship between the curing time and the undrained shear strength was approximated by a power function, which is used to predict the evolution over time of the effective yield stress, and Young’s modulus (with a correction factor of 0.4).

Firstly, the results of triaxial CIU tests, carried out for 28 and 90 days of curing time, were used to validate the constitutive model laws and the effect of curing time. Next, these models were used to predict the behaviour of an embankment built on a soft soil reinforced with DMCs. Some conclusions can be reached:

- The results of the triaxial CIU tests show that the numerical models are able to simulate the stress-strain behaviour until the failure of samples of the stabilised soil, for two curing times (28 and 90 days). However, the softening observed after the peak strength is not predicted by the models.
- Reinforcing the soil foundations with DMCs significantly decreases the settlement of the embankment.
- The curing time has a low impact on the settlement obtained, since the major part of the deformation occurs in the short term, due to the high stiffness of the DMCs.
- The increase of the curing time promotes a slight increase in the effective vertical stress, which is associated with a higher stiffness.

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