

Effects of early-age consolidation on strength development in cement-treated clay

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ABSTRACT

Consolidation of cement-treated high-water content clays during their initial curing stages is a rarely considered factor in design practice, due to the assumption that cement hydration progresses much faster than consolidation in clays under typical circumstances. Certain situations, however, seem to point to importance of early-age effective stress developments in treated ground when its interim and eventual shear strengths are evaluated. This study experimentally investigated manners in which cement-treated clays develop its yield stress and shear strength through interactions between bonding and densification when subjected to effective stress changes prematurely before the hydration processes are complete. The investigation involved a suite of undrained triaxial tests on cement-treated specimens that were cured under different isotropic stresses, supplemented by $K_0$ compression tests. The results suggested that apparently opposite consequences could be observed depending on the cement doses; reductions in undrained shear strength were observed when early-age consolidation occurred in clay treated with a larger cement dose, while the opposite was true for a smaller cement dose. These apparently complex effects seem to be only explained by kinematic development of a state bounding surface, which adjusts itself to a consolidation stress regime during curing.

Keywords: cement-treated clay, ground improvement, consolidation, structure, destructuction

1 INTRODUCTION

The standard practice of strength evaluation for cement-treated clays in most countries involves measuring unconfined compression strength of cored specimens and/or laboratoty-made ‘equivalents’. Significant differences are frequently observed, however, between the strengths of the above two types of specimens, regardless of adopted admixture execution techniques (PWRC, 2004; CDIT, 2008; Kitazume & Nishimura, 2012). Although the variability in original soil conditions and the inhomogeneity in insufficiently mixed materials are usually blamed for such incompatibilities, it is more rational to imagine that more than a few different factors are at play to different degrees of significance.

In evaluating cement-treated clays’ strength development, influence of effective stress increases due to the treated slurry’s self-weight or overlying structures (e.g. Consoli et al., 2000) is a rarely considered factor. This is particularly so with clays, in which consolidation is normally a slow process and may be considered as an independent process that occurs only after cement hydration is fully completed. However, there are situations in which early-age consolidation may play more than a secondary role. For example, slight undersaturation, as can happen with dry methods (i.e. cement dosed as powder), prompts an early transfer of the excess pore water pressure to the effective stress. It is indeed a common practice in Nordic countries, where dry methods are more common, to apply a modest surcharge (Åhnberg et al., 2001) on their often peaty surface soils soon after ground improvement. Also in cold regions, low ground temperature can significantly delay the cement-hydration processes (Kitazume et al., 2009). Such a situation would leave sufficient time for consolidation to progress, albeit not fully, before cementation becomes a dominant factor in the soil’s strength.

This study investigated how cement-treated clays develop its strength through interactions between bonding and densification when subjected to effective stress changes before the hydration is complete. Although the study has not been completed yet, the data obtained so far suggest that apparently complex manners in which the strength and stiffness evolve may be explained by hypothesised evolution of a state bounding surface involving cementation development, destructuring and ageing around a consolidation stress. This paper presents main experimental outcomes and an outline of the envisaged mechanism, without proposing a particular set of equations.
2 TESTING PROGRAMME AND TESTED MATERIALS

This study mainly reports results of undrained triaxial tests performed on stabilised clay specimens. The specimen size was 50 mm in diameter and 100 mm in height. A pair of bender elements were deployed at the bottom and top ends of the specimens to measure the shear modulus, \( G \), during the consolidation stages. This paper focuses only on the shear strength and the measured shear modulus is not discussed.

The tested soil was cement-treated alluvial clay with a modest amount of organic matters, with its properties shown in Table 1. It was firstly homogenised at \( w=85\% \) and then mixed with a cement-based binder especially designed for stabilising organic soils. The binder was dosed as slurry of 100\% water content. The adopted admixture contents, \( c/s \), defined as the admixture (cement) weight per dry soil weight, were 10\% and 15\%. After the binder-admixed samples were cured under humid conditions (RH-100\%) at 24\(^\circ\)C in plastic moulds for a few days, they were demoulded and then cured under different isotropic pressures according to the schemes illustrated in Figure 1. The curing under pressure was performed in a separate hydraulic chamber, with the specimens enclosed in rubber membranes. This method allowed multiple specimens to be cured simultaneously under pressure, without occupying the triaxial cell during the curing. Filter paper strips were attached to the lateral side of the specimens both during the curing and the testing. The dissipation of the pore water pressure generated by the pressure application is estimated to have completed within a few hours. The undrained compression was performed at 0.05\%/min after 91 days of total curing.

Table 1. Physical properties of tested clay.

| Property                  | Value   |
|---------------------------|---------|
| Natural water content, \( w_n \) (%) | 85      |
| Liquid limit, \( w_l \) (%)       | 78      |
| Plastic limit, \( w_p \) (%)       | 38      |
| Particle density, \( \rho \) (g/cm\(^3\)) | 2.57    |
| Ignition loss, \( L_i \) (%)       | 6.0     |

In addition to the triaxial compression tests, constant-rate-of-strain (CRS) \( K_0 \) consolidation tests were conducted on standard-sized (i.e. 60 mm-diameter and 20 mm-thickness) specimens. The adopted strain rate was 0.017\%/min. Considering that the triaxial specimens were all consolidated isotropically, it would have been ideal to ensure compatibility by obtaining isotropic, not \( K_0 \), compression curves. However, a limitation in applicable isotropic pressure in the authors’ laboratory would have allowed such curves to be obtained only to modest stress levels. Also included in this paper are the unconfined compression strengths of the specimens cured under atmospheric pressure. The adopted unconfined compression rate was 1\%/min and each reported result represents an average of three specimens with identical conditions.

3 CONSOLIDATION HISTORY AND STRENGTH DEVELOPMENT

3.1 Development of strength and yield stress during unconfined curing

The development of the unconfined compression strength, \( q_u \), and the consolidation yield effective stress in \( K_0 \) compression, \( \sigma_{vy}' \), is shown in Figure 2 against time after the binder admixing. The unconfined compression strengths for \( c/s=10\% \) and 15\% had attained 44\% and 68\% of the ultimate strength (defined at Day 91) by Day 7, respectively, and both reached 90\% by Day 28. Measurement of the yield stress \( \sigma_{vy}' \) for \( c/s=15\% \) was met with difficulty in ensuring sufficient consistency and repeatability. Although the most recently performed series (Batch 2; uncompleted yet to Day 91) seems to exhibit consistent results, additional investigation is necessary. For this paper, however, it suffices to find that \( \sigma_{vy}' \) for \( c/s=15\% \) was well over 400 kPa.

![Fig. 1. Stress histories applied to specimens during curing.](image1)

![Fig. 2. Unconfined compression strength, \( q_u \), and \( K_0 \) consolidation yield stress, \( \sigma_{vy}' \), of specimens cured under atmospheric pressure.](image2)
3.2 Yield and failure characteristics

The effective stress paths and the stress-strain curves obtained from all the triaxial compression tests are shown in Figure 3. All the specimens with $c/s=15\%$ behaved in a similar manner to un cemented over-consolidated clays, with the effective stress path heading towards convergence. A common critical state line with no apparent cohesion was not reached in the $q - p'$ plane even after strain-softening, although the stress-strain curves suggested that steady states were reached. The peak stress points for all the tests are replotted in Figure 4 along with their envelopes for each series. It is clear that the eventual strength envelopes after strain-softening still had significant apparent cohesion.

While the tests in Series 2 and 3 for $c/s=10\%$ exhibited broadly similar behaviour, those in Series 1 are conspicuously different; all the effective stress paths indicate the contractive characteristics typically seen in normally consolidated clays. Given the $\sigma_{vy}$ values of only 130-220 kPa for the samples with $c/s=10\%$, as shown in Figure 2, this is an expected result. It is similarly understood that the ‘over-consolidated behaviour’ seen in Series 2 and 3 with $c/s=10\%$ was indeed due to the mechanical unloading (see Figure 1). On the contrary, the similar behaviour observed in Series 1 with $c/s=15\%$ is not because of mechanical over-consolidation, as no history of unloading was applied. The increase of $\sigma_{vy}$ by the cement hydration, rather than a decrease of the effective stress, led to the pseudo-over-consolidated behaviour. For Series 2 and 3 with $c/s=15\%$, the above two factors (unloading and the $\sigma_{vy}$ increase) are considered to have had combined effects on the behaviour.

The 91-day unconfined compression strengths, $q_u$, as shown in Figure 3, is larger than the undrained shear strengths expected of a triaxial test starting from $p'=0$ for $c/s=15\%$, possibly due to the faster loading rate. However, the $q_u$ values (28-day strength is normally used in design) seem to provide broadly representative undrained shear strengths for consolidation stresses smaller than yield levels.

3.3 Influence of effective stress during curing on strength

The application of effective stress during the curing brought apparently opposite consequences to the shear strength in the cases with $c/s=10\%$ and 15\%. As shown in Figure 4, the earlier stress application led to the
higher eventual strengths for $c/s=10\%$, while the opposite was true for $c/s=15\%$. This difference can be partly explained by the magnitude of the stresses during the curing, 400kPa, in relation to the consolidation yield stress, $\sigma_{y'}$, at the moments of stress application. In the tests with $c/s=10\%$, the applied stress of 400kPa was well in excess of $\sigma_{y'}$, and possibly $p'_c$, at any moment of curing, as can be seen in Figure 2. The stress application therefore damaged the cementation that had already developed. The earlier application led to denser states as shown in Figure 5, as the specimens were still softer, and left further room for re-cementation by the remaining hydration processes at these denser states. Note that the continuous compression curves shown in Figure 5 were obtained from the $K_0$ compression conducted separately and the 91-day pre-shearing isotropic states in the triaxial tests, represented by the markers, do not necessarily lie on the 91-day $K_0$ curve.

For $c/s=15\%$, the applied stress of 400kPa is just sufficient to bring the early-age specimens to or close to yield but not the well-aged specimens. Therefore, the stress application might have been damaging only to the early-age specimens. Importantly, the earlier application of stress unanimously led to $q_{un}$ lower than the unconfined compression strength, $q_u$, suggesting that the normal practice of quality control through laboratory mix tests, without generous factors of safety usually set in practice, fails to provide safe design strengths in some situations.

4 CONCEPTUAL DESCRIPTION OF OBSERVED STRENGTH DEVELOPMENT

There have been some attempts to relate the shear strength of naturally structured or artificially cemented clays to their consolidation yield stress. Cotecchia & Chandler (2000) presented the ‘sensitivity-framework’, in which cementation effects are represented by an isotropic expansion of the state bounding surface by a factor $s$; sensitivity. Kasama et al. (2006) proposed normalisation of cement-treated clays’ strength based on an expansion of the state bounding surface towards both compression (i.e. positive $p'$ direction) and tension (i.e. negative $p'$ direction). In both concepts, if the expansion is isotropic, only a consolidation yield stress in any compression mode (e.g. $p'_c$ or $\sigma_{y'}$) is required to specify the bounding surface size and hence the strength. It was indeed reported by Åhnberg (2006) on stabilised Swedish peaty soils that the undrained strength and the $K_0$ yield stress, $\sigma_{y'}$, were closely correlated. However, these pictures do not seem to fit the authors’ experimental results, as will be explained subsequently. The cemented structures that develop under imposed effective stress are obviously not in the above studies’ scope.
Following the authors’ experimental results, additional series of $K_0$ compression tests have been undertaken to understand how the development of a state bounding surface is affected by simultaneous cementation, consolidation and ageing. Although the data are not presented here, it has been systematically found that an early application of effective stress in $K_0$ compression during cement hydration significantly increases the yield stress when the $K_0$ compression is resumed subsequently, overshooting the normal compression line for a sample cured unconfined (i.e. Series 1), as illustrated in Figure 6 (top diagrams). This behaviour can be partially recognisable in Figure 5 for the curing under isotropic stress too, where the state relationships from Series 2 and 3 tend to overshoot that from Series 1. It is clear that soils under simultaneous action of cementation and confinement develop more resistance against yield in the applied stress direction mode than expected under an individual action. If this observation is combined with the conventional strength normalisation by a single yield stress parameter, the shear strength hierarchy for $c/s=15\%$ seen in Figure 4 cannot be explained, as the hierarchy of the yield stress in isotropic compression is reverse.

The experimental results seem to be only explainable by considering a kinematic/translational evolution of the state bounding surface during yielding and cementation according to the direction of stress application. A hypothetical scenario is illustrated in Figure 6 (bottom diagrams). A stress application during cement hydration could bias the location of the state bounding surface (this is partially through disturbance to cementation during early consolidation), hence resulting in larger yield stress in the continuing loading direction but possibly smaller strength in some shear loading modes. Figure 6 (right diagrams) explains the Series 1-3 results for $c/s=15\%$ (Figure 4). The same mechanism is in play in the cases of $c/s=10\%$; however, the consequence is in contrast with that for $c/s=15\%$ cases. Given the eventually small $p'$ values due to the smaller binder dose, the late consolidation to 400 kPa on Day 91 disturbed by-then developed cementation significantly. In case of Series 1 for $c/s=10\%$, the volumetric strain reached 16\% at 530 kPa; sufficient to cause significant damages (e.g. Mašín, 2007; Xiao & Lee, 2014). However, the specimens that had undergone early disturbance had time to partially recover the cementation. This difference, according to Figure 6 (left diagrams), probably led to the strength hierarchy for $c/s=10\%$ seen in Figure 4.

Fig. 6. Hypothesised mechanism for state bounding surface evolution due to early consolidation (left: $c/s=10\%$, right, $c/s=15\%$).
5 CONCLUSIONS

The influence of applying stresses at early ages during curing on the shear strength of cement-treated clay was investigated through a systematic set of triaxial compression tests and $K_0$ compression tests. The shear strength could either be reduced or increased due to the stress application during the early stages of curing, depending on the binder amount and hence the cementation strength at the moment of the stress application. A potential mechanism for explaining this apparently complex effect was hypothesised and expressed with assumed but plausible evolution of the state bounding surface characterised by damaging-induced and consolidation stress-biased kinematics. The hypothesised mechanism obviously requires more experimental corroboration to be fully accepted, but the observations in this study have some direct implications to soil stabilisation practice; there is no single answer to a question “is it a good thing to apply stress while the treated soil is still half stabilised?” With proper understanding of the stabilised soils’ characteristics of yield and strength evolution, it may be possible to exploit extra strength increases by early consolidation (at the expense of modest deformation or settlement). Alternatively, inappropriately applied premature loading may also lead to eventually lower shear resistance in certain shear modes.

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