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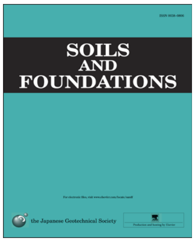

SOILS AND FOUNDATIONS

Yielding of cement-treated marine clay

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Abstract

This paper presents the findings of an experimental study on the primary yielding and post-yield behavior of cement-treated Singapore marine clay. The study was conducted using unconfined compression tests and triaxial tests. The results show that all the primary yield loci for the cement-treated marine clay have a consistent shape regardless of the mix ratio, curing stress or curing period. Three relationships are proposed for determining the size of the primary yield locus. The first two involve the direct determination of the isotropic primary yield stress, whereas the third makes use of the unconfined compressive strength. The first two relations are valid only for 7-day specimens. The third appears to have slightly larger scatter, but it is also applicable over a wider range of curing period and curing stress. Post-yield, over-consolidated samples were obtained by compressing specimens isotropically under effective stress levels higher than their isotropic primary yield stress and then allowing them to swell back to a lower effective confining stress prior to shearing. The normalized yield loci of these pre-yielded samples show a "collapse" from steep arches to more-rounded ellipses, while the yield loci expand with isotropic pre-compression pressure.

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Keywords: Cement-treated clay; Primary yielding; Yield locus; Unconfined compressive strength; Triaxial test; Tension cut-off

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1. Introduction

Cement-admixtures are commonly used for improving soft fine-grained soils. The strength and failure envelopes of cement-treated soft clay, as well as the factors affecting them, have been studied extensively (e.g., Kawasaki et al., 1981; Gallavresi, 1992; Yoshizawa et al., 1996; Yu et al., 1998; Miura et al., 2001; Horpibulsuk et al., 2003, 2006, 2011; Lee et al., 2005; Consoli et al., 2006; Namikawa and Koseki, 2006; Kasama et al., 2007; Kongsukprasert et al., 2007; Chiu et al., 2008; Ezaoui et al., 2010; Rabbi et al., 2011; Seng and Tanaka, 2011). Other studies have also examined the isotropic compression and the drained and undrained shear behaviour of cement-treated soils (e.g., Hirai et al., 1989; Matsuoka and Sun, 1995; Uddin et al., 1997; Kasama et al., 2000, 2006; Rotta et al., 2003; Bergado et al., 2006; Namikawa and Mihira, 2007; Taheri et al., 2012). More recently, the strength and deformation characteristics of soils cemented with other stablization materials have been investigated (e.g., Horpibulsuk et al., 2013; Yasuhara et al., 2012; Kamei et al., 2013; Vichan and Rachan, 2013). The physico-chemical and micro-structural aspects of cement-treated Singapore marine

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Table 1
Summary of specimen mix ratios and curing conditions in this study.

Mix ratio (S–C–W)	Soil–cement ratio (S:C)	Water–cement ratio (W:C)	Water content C_w (%)	Curing load p'_{cur} (kPa)	Curing time t (days)	Tests in this study
10–1–11	10:1	11:1	100	0–350	7–28	UCT[*], ICT[†], CIU1;[‡], CID2;[§]
20–3–23	20:3	23:3	100	0–250	7–210	UCT, ICT, CIU, CID, SP3;[‖]
5–1–6	5:1	6:1	100	0–250	7–180	UCT, ICT, CIU, CID, SP
10–3–13	10:3	13:3	100	0	7–28	UCT, ICT, CIU, CID, SP
10–3–17.3	10:3	17.3:3	133	0–100	7–28	UCT, ICT
10–3–19.5	10:3	19.5:3	150	0–100	7–28	UCT, ICT
2–1–3	2:1	3:1	100	0	7–28	UCT, ICT, CIU, CID, SP
2–1–4	2:1	4:1	133	0–250	7–180	UCT, ICT, CIU, CID, SP
2–1–4.5	2:1	4.5:1	150	0–100	7–100	UCT, ICT
2–1–5	2:1	5:1	167	0–200	7–28	UCT, ICT, CIU, CID
2–1–5.5	2:1	5.5:1	183	0	7–28	UCT, ICT, CIU, CID
1.3–1–3.06	1.3:1	3.06:1	133	0–100	7–28	UCT, ICT
1.3–1–3.45	1.3:1	3.45:1	150	0–100	7–28	UCT, ICT
1.3–1–3.5	1.3:1	3.5:1	152	0–100	7–28	UCT, ICT, CIU, CID
1–1–2	1:1	2:1	100	0–100	7–28	UCT, ICT, CIU, CID
1–1–2.66	1:1	2.66:1	133	0–100	7–28	UCT, ICT
1–1–3	1:1	3:1	150	0–100	7–90	UCT, ICT
10–1–7.9	10:1	7.9:1	72	0–100	7–28	UCT, ICT
6–1–5	6:1	5:1	71	0–100	7–28	UCT, ICT
4–1–3.6	4:1	3.6:1	72	0–100	7–28	UCT, ICT

[*] Unconfined compressive strength test.
[†] Isotropic compression test.
[‡] Isotropic consolidated undrained compression test.
[§] Isotropic consolidated drained compression test.
[‖] Constant stress ratio test.

clay (e.g., Chew et al., 2004; Chin, 2006; Kamruzzaman et al., 2009) have also been studied. However, their results are qualitative and restricted to a few mix ratios, mostly with cement contents of about 20% or lower.

Although a few constitutive models for cement-treated clay have been proposed, their yield surfaces were assumed to be the same as those for natural soils (e.g., Lee et al., 2004; Suebsuk et al., 2010; Horpibulsuk et al., 2010). This may be attributable to the dearth of data on yielding and post-yield behaviour of cement-treated clay, particularly for admixtures with high cement contents. Theoretically, yielding is readily defined as the onset of irrecoverable or plastic strain. However, this is often difficult to discern experimentally. Hence, yielding is usually identified by a discontinuity in the stress–strain behavior (Vaughan, 1988; Maccarini, 1987; Bressani, 1990; Jardine et al., 1991; Jardine, 1992; Smith et al., 1992; Malandraki and Toll, 1996; Leroueil and Vaughan, 1990; Bergado et al., 2006) or an abrupt decrease in stiffness (e.g., Mitchell, 1970; Wong and Mitchell, 1975; Callisto and Calabresi, 1998; Coop and Atkinson, 1993; Rotta et al., 2003; Jongpradist et al., 2011) under monotonic stress changes. This discontinuity or abrupt decrease is more significant for structured soil, and it is taken to signify the onset of the loss of structure in the soil. This point is known as primary yield. As the structure is due to cementation for cement-treated soil, the primary yield indicates the beginning of the loss of bonding in the soil.

There are different ways to identify and to determine primary yielding. For example, the primary yield is taken to occur at the point at which the compression curve starts to deviate from the initial linear behaviour (Rotta et al., 2003; Coop and Atkinson, 1993). Cotecchia and Chandler (2000) defined an alternative 'gross yield point' as the point of tangency between the compression curve and a line drawn parallel to the intrinsic compression line (Burland, 1990), at which the ratio of the stress on the compressive curve to that on the intrinsic compression line is maximum.

Loss of structure (or bonding in cement-treated soil) after primary yielding (Leroueil and Vaughan, 1990) is progressive with additional straining. This is termed herein as post-yield behavior. For cement-treated soil, this post-yield behavior involves a gradual loss of bonding with strain after primary yielding. This paper presents the results of tests on the primary yield and the post-yield behaviour of cement-treated Singapore marine clay, based on triaxial tests conducted over a wide range of mix ratios and different curing conditions. The results show that, regardless of mix ratios and conditions, the primary yield loci have a generic shape. The size of the yield locus is shown to be well-correlated to the unconfined compressive strength, which in turn can be correlated to the mix ratios and conditions.

2. Experiment investigation

2.1. Materials

Specimens were prepared from Singapore Upper marine clay and Ordinary Portland Cement (OPC). The marine clay

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