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Behaviour of clay treated with cement & fibre while capturing cementation degradation and fibre failure – C3F Model

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ABSTRACT

Soil treated with cement becomes brittle because its shear strength decreases rapidly in a post-peak state, which is why in recent years the inclusion of fibre into soil treated with cement has become an increasingly popular research area. This paper presents a constitutive model to simulate the behaviour of the fibre reinforced cement treated soil, referred to as the improved soil composite. In this model, a non-linear failure envelope was formulated to merge with the Critical State Line (CSL) of the reconstituted soil mixture at high levels of stress in order to capture the broken cementation bonds and ruptured fibre. A non-associated plastic potential function and a general stress strain relationship that includes the softening of the composite soil were also proposed to simulate the pre-and-post peak state.

Moreover, many researchers focus on the addition of fibre into sand, soft clay, and sand treated with cement, whereas the behaviour of soft clay treated with fibre and cement requires further investigation. Hence, in this study a series of undrained triaxial tests were carried out on natural Ballina clay treated with cement and 0.3%–0.5% of fibre to determine how the amount of fibre and cement affects the behaviour of soft clay. SEM images were also analysed to study the structure of the improved Ballina composite at the microstructural level. The laboratory results indicated that the combined effects of cementation and fibre reinforcement increased the shear strength and ductility of treated soft clay. Under triaxial conditions the peak shear strength of soft clay treated with cement and fibre increases dramatically due to the formation of cementation bonds and the bridging effect provided by the fibres, and the brittleness caused by the cementation bonds breaking also improves significantly due to the inclusion of fibre. However, when shearing at a high mean effective stress the cementation bonds break and the fibre ruptures due to the mean effective stresses and plastic deviatoric strain which caused major cracks to appear within the sample.

The performance of the model was evaluated by comparing its predictions with the results of the undrained triaxial tests conducted on the improved Ballina clay composite. By capturing the main features of the composite soil the model provided reliable predictions that agreed with the experimental results.

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1. Introduction

With the increasing growth in population and subsequent economic activities, construction over soft or weak soils has become popular, leading to the development of various techniques to improve the properties of soft soil. Over the years, deep soil mixing where in-situ soil is mixed with cement or lime to improve the strength and compressibility of the base soil has proven to be an effective technique for improving soft ground (Horpibulsuk, 2001; Kamruzzaman et al., 2006; Topolnicki, 2004). The contribution that cement makes to the behaviour of soft soil has been investigated extensively by researchers such as Chew et al. (2004), Horpibulsuk et al. (2004), Kamruzzaman et al. (2009), Lorenzo and Bergado (2004), Porbaha et al. (2000) and Tan et al. (2002). The formation of cementation bonds due to a chemical interaction between the cement and soil particles increases the strength and restricts the compressibility of the clay, unlike un-treated soil (Kamruzzaman et al., 2009; Lorenzo and Bergado, 2006; Uddin et al., 1997), but as Lorenzo and Bergado (2006), Panda and Rao (1998), Porbaha et al. (2000) and Yin (2001) reported, in a post peak state, treated soil becomes very brittle as the residual strength of the soil drops after failure. Moreover, the cementation bonds break due to volumetric and deviatoric strains, and they also increase the brittleness of cement treated clay.

In recent years, geosynthetics such as fibre, geogrid, or geotextile have been used as effective and reliable reinforcements for soft soil (Consoli et al., 2004; Tang et al., 2007). According to Tang et al. (2007), fibres are randomly and easily mixed with soft soil, which strengthen the potential weakness planes, unlike geogrid or geotextile, as suggested by Jiang et al. (2010). Moreover, researchers such as Cai et al. (2006), Diambra et al. (2013), Fatahi et al. (2012), Li and Ding (2002), Michalowski and Cermák (2003), Tang et al. (2010), Yilmaz (2015) and Zornberg (2002) have carried out numerous studies to investigate the inclusion of fibre in soft soil or soil treated with cement, and discovered that fibre improves its overall performance by increasing the peak shear strength and residual strength of both cohesive and cohesionless soil. Recently, Botero et al. (2015) reported the effect of fibre inclusion in improving the ductility of silty clay using polyethylene terephthalate, a recycled fibre from plastic waste such as plastic bottles and containers. Researchers such as Consoli et al. (2010), Hamidi and Hooresfand (2013) and Park (2009), based on the results of experiments on cement treated sand reinforced with fibre, concluded that brittleness decreased due to the fibre reinforcement. Most previous studies only investigated how the inclusion of fibre affected cement treated and un-treated cohesionless soils, while studies on the behaviour of cement treated clayey soils improved with fibre are limited which few researchers such as Cai et al. (2006), Chen et al. (2015) and Tang et al. (2007) focused on this area. It was found that the peak and residual strengths of cement treated clay improve due to the addition of fibre (Cai et al., 2006; Tang et al., 2007). Moreover, various factors affecting the improvement in the strength of the treated clay include the fibre type, fibre length and the content of fibre and cement, as suggested by Chen et al. (2015).

Although the presence of randomly oriented fibres influences the macroscopic behaviour of the soil composite contributing to structural anisotropy, many researchers have assumed isotropy for simplicity during analysis. In a review of fibre reinforced soil, Hejazi et al. (2012) reported that soil isotropy is assumed to be sustained by randomly distributed fibre in the soil matrix. However, Diambra et al. (2010) suggested that the preferred plane of orientation of the fibre is sub-horizontal when common methods such as moist tamping or vibration are used in preparing the reinforced sample in the laboratory. Moreover, practical applications often require compaction by rolling of fibre reinforced soil which creates the horizontal bedding plane (Michalowski and Čermák, 2002). Such preferred orientation of the fibre leads to anisotropy in the behaviour of the improved soil composite as suggested by Michalowski and Čermák (2002). Moreover, the fibre orientation may result in the principle stress and strain axes being rotated or non-coaxiality as suggested by Diambra et al. (2010) and Michalowski (2008). Furthermore, in analysing the failure of the fibre reinforced soil, Michalowski and Zhao (1996) assumed that the contribution of fibre to the shear strength is effective when subjected to tension while the fibre plays no role in compression as the fibre may buckle or kink. Michalowski and Čermák (2002) observed the kinematic hardening effect at large strains of the fibre reinforced sand as a result of random distribution of fibre. The importance of fibre orientation induced anisotropy leads to the development of models similar to Diambra et al. (2010) model.

Furthermore, Tang et al. (2007) explained that the inclusion of fibre into the compacted matrix of soil-cement clusters formed by hydration and pozzolanic reactions in the cement, increased the load transfer between the matrix and the fibre. As loading begins, the normal stresses acting on the fibre increase the pull out resistance as well as the friction and interlocking forces at the interface, but during loading, small cracks are formed within the soil matrix as the cementation bonds gradually break. At this stage the fibre is mobilised as frictional and interlocking forces are distributed along the length of the fibre, such that large cracks appear within the soil matrix at failure and tensile resistance from the fibre increases the connection between the fibre and cementitious products, which prevents the development of any further cracks (Tang et al., 2007). Thus, brittle failure of the cement treated soil becomes more ductile due to the bridging effects provided by the fibre reinforcement. However, the failure mechanisms of fibre, including the pull-out response and possible breakage, on the behaviour of improved soil require further investigations, particularly under triaxial conditions. Thus, in this paper a series of undrained triaxial tests were carried out on natural Ballina clay treated with 15% cement and 0%, 0.3% and 0.5% of fibre, under different confining pressures to investigate how varying the amount of fibre affected the improved soil composite.

In addition, a constitutive model is needed to simulate the behaviour of cemented clay improved with fibre under various loading conditions, so constitutive models such as the Cemented Cam Clay (CCC) model by Nguyen et al. (2014), the Modified Structured Cam Clay (MSCC) model proposed by Suebsuk et al. (2010), or a constitutive model by Horpibulsuk et al. (2010) have been developed for soil treated with cement. Although these constitutive models can simulate the hardening behaviour of the cement treated clay up to the peak state, they used negative hardening rule for the post peak state. Zhu et al. (2010)