Experimental and numerical investigate on single fiber pull-out from cement stabilized soil

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ABSTRACT: Failure mechanism of short fiber-reinforced cement-stabilized silty clay depends on the interaction between the fiber and the cement-stabilized soil matrix. And the mechanism of fiber reinforcement is revealed by experimental studies and numerical simulations. Firstly, by using the single fiber pull-out test, the results show that the maximum tensile force of single fiber under different embedding lengths increases with the development of age. Then based on cohesive model, a three-dimensional finite element method model is established to simulate the interaction between single fiber and cement-stabilized soil. The comparisons of theoretical results, numerical results and experimental results reflect that viscous interface parameters have vital effects on the interaction between single fiber and cement-stabilized matrix. Introducing the proper cohesive model, numerical results agree well with the experimental results better.

Keywords: fiber reinforced; cement stabilized soil; single fiber pull-out; debonding; pull-out curve; finite element method; viscous contact

1 INTRODUCTION

The fibers can inhibit the expansion of cement-stabilized soil, also can improve crack resistance and long-term strength. In recent years, a large number of researchers studies the cement-stabilized soil reinforcement formula (Consoli et al. 2011; Tang et al. 2007; Chen et al. 2015) by means of experiments in order to get better effects. According to the experiments, the reinforcement effects mainly depends on six factors: fiber volume fraction, fiber orientation, fiber shape, fiber material properties, matrix material properties, and surface contact characteristics of fiber and matrix (Ellis et al. 2014). And the understanding of the mechanism of fiber and matrix interaction relies on the single fiber pull-out test, which is a critical problem to decide the role of fiber and its reinforcement effects, and it is also the key point that researchers and engineers have been concerning about. For the accurate measurement of single fiber pull-out curves, many researchers have developed a variety of advanced precision apparatus for single fiber pull-out tests (Hampe et al. 1995; Geng & Leung 1996; Chan & Li 1997; Lecompte et al. 2015). For further insight of fiber and matrix interactions, Cox introduced the shear lag model to established the mathematical model of fiber and matrix interaction (Cox 1952), which solving stress field and strain field of the composite. Based on the shear lag model or more rigorous three-dimensional model of interaction between fiber and matrix, a large number of research results are obtained by the following researchers (Greszczuk 1969; Bartos 1980; Wang et al. 1988). The two-dimensional theory of fiber pull-out process has been described in the reference by Lawrence's solution (Lawrence 1972) and the three-dimensional axisymmetric description can refer to research results of Gopalaratnam (1987). But their solutions are under consideration of the friction between fiber and matrix without viscous contact in the process of debonding, which leads to the problem that the theoretical simulation results are different from the experimental results. It is well known that the interfacial viscous effects is very important for the interaction analysis between fiber and matrix, Hsueh (1991) considered viscous effects in the interface and the radial shrinkage in fiber pull-out process caused by the Poisson effect, he only analyzed the viscous stress transfer for fully bonded between the interface of fiber and matrix without considering the effects of interfacial debonding process, and due to the consideration of the Poisson effect at the same time, the non-linear equation cannot be solved analytically, and it requires to be analyzed through the Runge-Kutta numerical methods. These theoretical analyses are only applicable to simple shapes and boundary conditions, they are inconvenient for application in more complicated conditions. However, it can easily change fiber length, diameter, surface properties, and constitutive model and other conditions by the numerical method, and it was adopted by more researchers. Morrison used the method of preset debonding length to establish the two-dimensional finite element model to calculate the results of fiber debonding and pull-out force, and he found that the effects of fracture energy release rate G and fracture length b was significant for failure modes. When the b/R was greater than 16, the energy release rate curve was approximately horizontal, and this result was basically consistent with the analytical expression (Morrison 1988). Povirk (1993) developed a single fiber quasi static analysis depending on friction constitutive relation of pull-out rate, reflecting fiber and matrix interface friction velocity weakening. The above analysis of the interaction between fiber and matrix ignored the viscous contact condition at the interface, and the simulation results needed to be improved further.

In this paper, the interaction between polypropylene fiber and cement-stabilized soil matrix is studied and the law of the interaction with the age of cemented soil is analyzed. At first, through the pull-out experimental study of single polypropylene from cement-stabilized soil, it discusses the influence of the embedded fiber length and curing ages on the interaction between fiber and matrix, then establishes three-dimensional numerical calculation of axisymmetric finite element model for single fiber pull-out with viscous contact, at last, numerical simulation of fiber pull-out from matrix are conducted to compare to the experimental curves.

2 MATERIALS AND EXPERIMENTAL METHODS

2.1 *Experimental materials*

The silty clay for test was taken from a foundation pit in tideland reclamation area in Changzhi island, Zhoushan city. The curing agent is Conch No.325 Portland cement. Admixture adopted the ultra-fine silica powder material made by Co. Ltd. Chengdu Huiye, the particle size is 0.1-0.2μm, and its main component is amorphous silica which the dosage of SiO2 is over 95%. The water cement ratio of the prepared sample is 0.5, the ratio of cement to silica fume is 4:1, and the blending ratio of admixture is 15%. The reinforced material adopts polypropylene fiber, and cuts into fine fiber width of 2mm. During the experiment, the remolded soil was uniformly mixed with the prepared cement slurry and the fiber in a certain proportion. And then these mixtures were pressed into a soil sample mold to make of the needed soil samples. Fiber dosage was controlled by weight percentage of 0.05%, 0.1% and 0.2%, and three kinds of embedded length was 5 mm, 10 mm and 15 mm. The fibers were implanted into cement stabilized matrix using an embedding fiber method.

2.2 *Experimental equipment*

The experimental instruments mainly have the soil direct tensile test instrument(STZLY-1, Zhejiang geotechnical Instrument Manufacturing Co., Ltd.), geotechnical triaxial test apparatus, cement standard curing box with constant temperature and humidity (SHBY-40B, Zhejiang Shangyu Fuxiang geotechnical instrument factory), ZNLBS micro sensor of tensile force made by Bengbu Zhongnuo sensor Co., Ltd (range from 0 to 10N), the electronic scale, dial indicator, mold, magnetic table accessories etc.

2.3 *Experimental method*

The single fiber pull-out experiment was carried out in this paper. The interactions of fiber and matrix with different lengths of fiber are analyzed by the pull-out experiments under different curing ages. For tensile force of fiber pull out from matrix is impacted by the deformation modulus of the matrix, unconfined compressive strength was tested by a three-dimensional compressive instrument without confined stress (σ_3=0) to obtain the deformation modulus of the composites.
By installing with “S” type micro dynamometer on the soil direct tension tester, the single fiber pull-out experiment was carried out and the relationship between pull-out force and pull-out displacement in fiber pull-out process can be obtained. The effects of fiber length and the curing age of matrix on fiber matrix interaction was analyzed. Before the experiment, the half 8 shape specimens were prepared according to the shape 8 specimen preparation method and the experimental plan. Polypropylene fibers with three dif-

ferent lengths of 5mm, 10mm and 15mm are embedded in the specimens, the width of the single fiber is 2mm, the thickness is 0.04 mm, the sample is half of the mold, and its area is 30 cm^2, as shown in Figure 1. Specimens cured in cement standard curing box and carried out single fiber pull-out test at the 3th day, the 7th day, the 28th day and the 90th day, respectively.

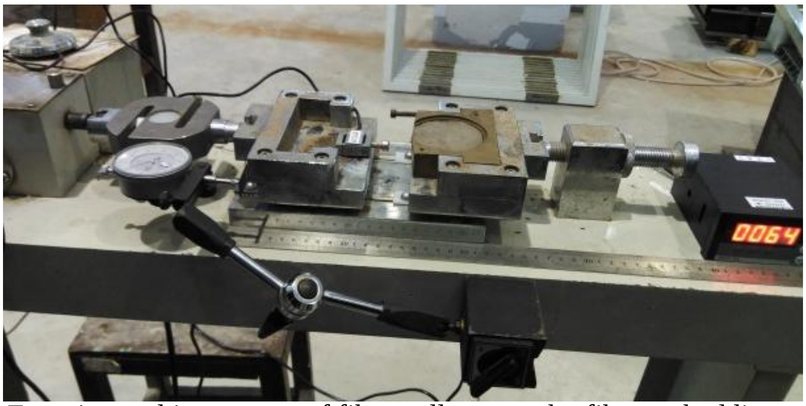


Figure 1. Experimental instrument of fiber pull-out test by fiber embedding method

The matrix deformation modulus test was carried out by unconfined compressive strength test. The cylinder specimens were used with diameter 39.1mm, height 80mm in this experiment. After the sample was made, it was wrapped in a plastic film and placed immediately into a humidity maintenance chamber with a temperature of 20℃±2℃ and relative humidity of more than 95%. The compressive strength test was carried out on the triaxial loading apparatus according to soil test method standard (GB_T50123) after solidifying to the corresponding curing ages in the curing tank. At the same time, the strain should be measured and the stress-strain curves should be plotted.

3 EXPERIMENTAL RESULTS AND ANALYSIS

3.1 *Analysis of single fiber pull-out test results*

Table 1 lists the average maximum pull-out force at different curing time under three fiber embedded lengths. And the curves of those relations are plotted in figure 2. Obviously, the maximum pull-out force gradually increases with the curing age before the 28th day, and the growth rate is relatively fast. After the 28th day, the pull-out force growth slows down, especially the growth rate of 5mm short fiber is less than 0.02N/d. The longer the fiber is, the greater the maximum pull-out force is. And when the fiber length increases from 5mm to 10mm, the maximum pull-out force increases more than 65% at the 90th day. When the fiber length continues to increase to 15mm, the fiber length increases by 50%, however, the maximum pull-out force is only about 20% higher than that of 10mm fiber, which shows that when the fiber increases from a short value to a certain value, the pull-out force increases rapidly, but once it exceeds a certain value, the growth rate of the fiber decreases significantly. This phenomenon shows that the fiber pull-out force is too low when the fiber is too short to conducive the development of the fiber strength. And the fiber also should not be too long because the pull-out force growth rate is lower when the fiber is too long, the benefit is not obvious.

Table 1. Test results of average maximum pull-out strength of single fiber.

Fiber embedded length（mm）	Pull-out force of the fiber（N）			
	3^{th} day	7^{th} day	28^{th} day	90^{th} day
5	0.82	1.34	2.40	3.56
10	1.59	1.62	3.97	5.90
15	1.77	2.07	4.71	7.10

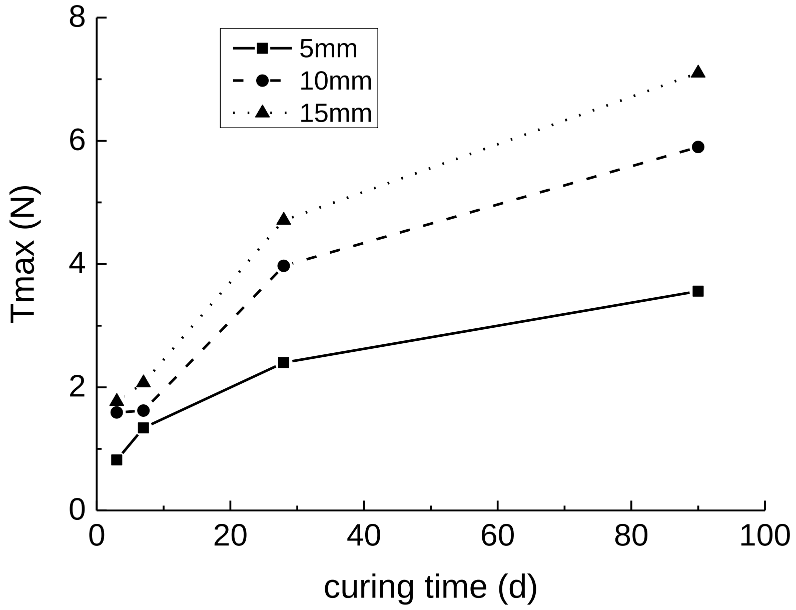
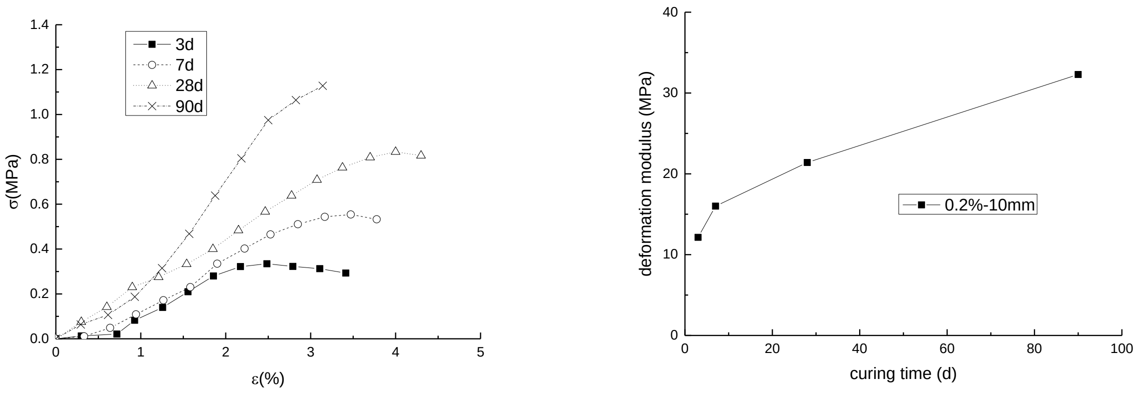


Figure 2. Relations between maximum pull-out force and curing age at different embedded lengths

3.2 *Experimental results and analysis of matrix deformation modulus*

The deformation modulus of matrix has significant influence on the interaction between fiber and matrix, and the modulus of deformation is closely related to the age of cement soil. With the solidification of cement, the change of the cement soil strength and deformation modulus is obvious. Unconfined uniaxial compressive strength test was studied with four different ages. The stress-strain curves are plotted as shown in Figure 3.

Figure 3(1) shows the stress-strain curves with 0.2% fiber dosage and 10mm length fiber of cement soil samples under different curing time, it can be seen that the strength of the sample increases continuously with the increase of age. The strength of the samples reach 0.8MPa at the 28th day and reach 1.1MPa at the 90th day. The strain of damage increases to the maximum at the 28th day, closing to 4.5%, but decreases significantly at the 90th day, even less than the strain at the 3th day, and lower than 3.5%. By taking the secant modulus at the midpoint of the stress-strain curve as the deformation modulus, the curve of the deformation modulus of matrix with the curing age is obtained. As shown in Figure 3(2), it can be seen that the deformation modulus increases with the development of age, the growth rate is fast from the 3th day to the 7th day, after that the growth rate declined slightly, but still maintain a rapid growth with approximately linear development.



(1) (2)

Figure 3. Effect of age on the stress-strain curves and deformation modulus(0.2% dosage and 10mm length)

4 EXPERIMENTAL ANALYSIS AND DISCUSSION

In this section, the numerical analysis of single fiber pull-out behavior of fiber reinforced cement soil is investigated. The influence of viscous contact parameters on the interaction between fiber and cement soil matrix is discussed in detail. The modulus of elasticity of the fiber is 700MPa. Because of the friction and damping effects between the fiber and the geotechnical engineering interface, there is a no thickness boundary layer, and the viscous contact of the single fiber pull-out process is simulated. Due to the complex mechanical properties of the composite interface, the cohesive force mainly includes cementation force, bite force, viscous and friction resistance. Before the fiber does not appear to debond, the cementation force and bite force play a major role, once the fiber appears debonding or sliding, viscous force and friction to undertake the main tension, so the viscosity and friction should be adopted under consideration of the interface contact properties. The friction interface between the fiber and the matrix is set as penalty contact with friction coefficient is 0.3, the bottom surface of fiber has no friction. The mechanical properties parameters of viscous effect are listed in Table 2.

Table 2. Mechanical parameters of viscous contact surface.

Viscous behavior	K_{nn}	K_{ss}	K_{tt}		
	1	1	1		
damage bahavior	Normal only	Shear-1 Only	Shear-2 Only	Fracture energy(N/mm)	Viscous coefficient
	1	1	1	5	0.00001

The fiber used in the pull-out test is a flat fiber. In order to making it easier to compare with the three-dimensional axisymmetric model, the area equivalent method is adopted to convert the fiber into a circular section. The geometric parameters of the model is matrix radius of 4mm, matrix length of 20mm, and fiber radius of 0.16mm. The fiber lengths are consistent with the pull-out test of 5mm, 10mm and 15mm, respectively. The elastic moduli corresponding to the 3th day, the 7th day, the 28th day and the 90th day are 60MPa, 80MPa, 100MPa and 160MPa, respectively, which approximately 5 times of the deformation modulus under the different curing age. The fiber length is 10mm, if not otherwise specified, and other parameters are the same as table 2.

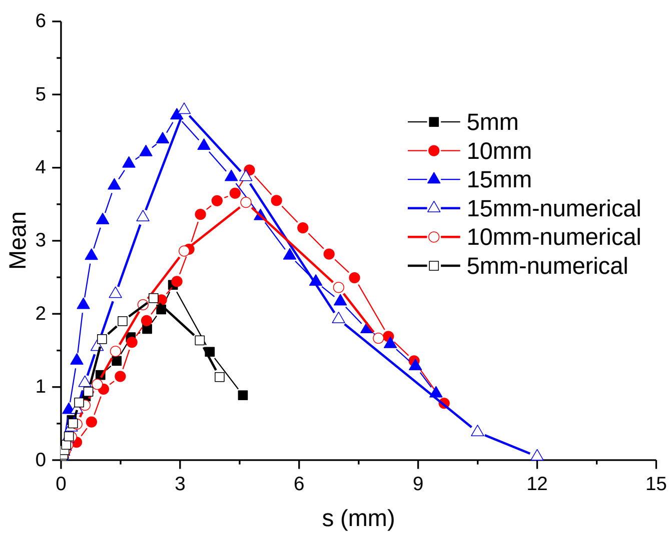


Figure 4. Pull-out curves of different fiber lengths at the 28th day compared with numerical results

It can be seen from figure 4 that the interaction between fiber and matrix under the viscous contact condition can be agree well with the experimental results at the 28th day. The peak value of pull-out curves, the rising and falling stage, and final residual value are basically consistent with the experiment.

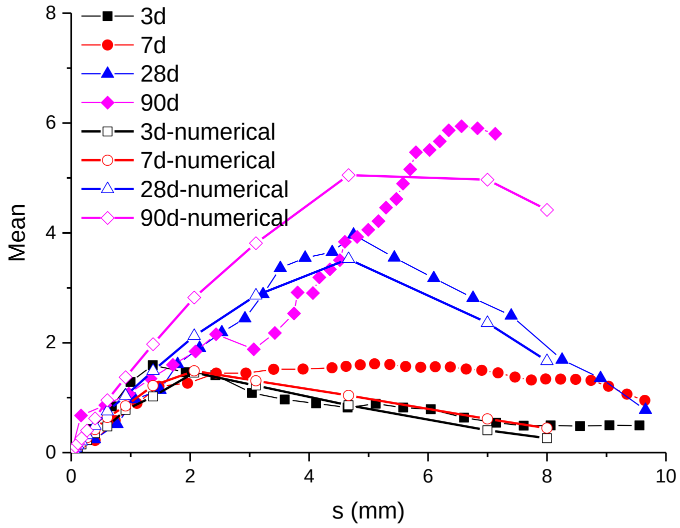


Figure 5. Numerical comparison of pull-out curves at different ages in fiber length of 10mm

It can be seen from Figure 5 that the numerical simulation results of viscous contact at different ages can be basically in good agreement with the results of fiber pull-out test, however, there are major differences in the 90th day. The main reason is that some of the fibers are broken in the pull-out experiment at the 90th day, whereas the numerical model of this paper does not consider fiber fracture, so as to cause a certain difference between the numerical results and the experimental results.

5 CONCLUSIONS

Based on the single fiber pull-out test of cemented soil, we obtained the relationship between fibers maximum pull-out force and curing ages at three embedding lengths. And the experimental results reflect the fact that the age of cemented soil and fiber embedded length play an important role in the interaction between the fiber and the matrix.

Numerical results of three-dimensional finite element model under consideration of viscous contact proved that the viscous contact parameters have significant effects on single fiber pull-out force. According to the comparison between numerical simulation of fiber pull-out from matrix and experimental curves, it can be founded that the calculation results of viscous contact model and pull-out experimental results can achieve better fitting effect, so the viscous contact between the fiber and the cemented soil is the necessary parameters for the analysis of fiber and matrix interaction.

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