CHEMICAL ENGINEERING TRANSACTIONS

VOL. 66, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Songying Zhao, Yougang Sun, Ye Zhou

ISBN 978-88-95608-63-1; **ISSN** 2283-9216

DOI: 10.3303/CET1866186

Effects of Different Porosities on Shear Strength of Fiber Clay by Response Surface Methodology

Chunpeng Han[a], Jiayi Tian[a], Jian Zhang[a], Yulong He[b,*]

[a]School of Civil Engineering, Northeast Forestry University, Harbin 150040, China
[b]China School of Transportation, Jilin University, Changchun 130012, China
heyl15@mails.jlu.edu.cn

To study the effects of different factors (fiber length, fiber content and porosity) on the shear strength of fiber reinforced soil, the direct shear test of 3 levels and 3 factors was designed by response surface methodology (RSM) to explore the effects of different factors on the increment of shear strength parameters and construct polynomial regression equation of each effect factor. The test results showed that internal friction angles of fiber soil and plain soil were very close in different porosities, and increment of cohesion was changed after mixing fiber. From the analysis of variance (ANOVA), fiber content was the main factor, followed by porosity, and the fiber length and porosity had strong interaction significance; the validity of the theoretical model of fiber pull-out in soil was checked. From the test, the porosity variable influenced the effect of fiber reinforced soil cohesion, and porosity of soil should be considered in the engineering program of fiber reinforced soil.

1. Introduction

Aim to fiber reinforced soil technology Researchers have studied how to obtain the optimum mix ratio of fiber soil by mixing different fibers in the different soils to enhance its strength and the ability to resist deformation. Y. Yilmaz (2015) investigated the effects of discrete polypropylene fibers and Class C fly ash on the stress–strain and shear strength behavior of clayey soil. Pradip et al., (2012) investigated the effects of random inclusion of polypropylene fibers on strength characteristics of cohesive soil. Shao et al., (2014) investigated the mechanical properties of sands reinforced with discrete randomly distributed fiber. Wu et al., (2015) investigated the mechanical properties of randomly distributed sisal fiber reinforced soil. Butt et al., (2016) investigated the strength behavior of clayey soil reinforced with human hair as natural fibers. Zaimoglu et al., (2012) investigated the strength behavior of fine-grained soil reinforced with randomly distributed polypropylene fibers. Qu and Sun, (2016) investigated the strength behavior of Shanghai clayey soil reinforced with wheat straw fibers.

2. Materials and methods

2.1 Materials

Table 1: Physical properties of soil samples

Specific gravity Gs	Maximum dry density ρ_d(g/cm^3)	Optimum water content ω_{opt} (%)	Liquid limit ω_L (%)	Plastic limit ω_P (%)	Plasticity index I_P (%)
2.65	1.86	11.4	33.3	24.0	9.3

Table 2: Physical and mechanical parameters of polypropylene

Density (g/cm^3)	Breaking tensile strength (MPa)	modulus of elasticity (MPa)	elongation	Diameter (μm)	Melting point (℃)
0.96	500	3850	10-28	18-48	165

Please cite this article as: Han C., Tian J., Zhang J., He Y., 2018, Effects of different porosities on shear strength of fiber clay by response surface methodology, Chemical Engineering Transactions, 66, 1111-1116 DOI:10.3303/CET1866186

The test soil sample was taken from a construction foundation pit in Harbin. The main physical parameters of sample soil used in test were provided in Table 1. Fiber used in the test is regular engineering polypropylene fibe. The main physical and mechanical parameters of the polypropylene fiber were given in Table 2.

2.2 Preparation of sample and test

The soil samples obtained from the foundation pit were naturally air-dried, then crushed for screening with a 2mm sieve. The best water content of the soil compaction test was used, and water, soil and fiber were then mixed evenly. The fiber length was 3mm, 6mm, 9mm, 12mm and the quality percentage of the dry soil was regarded as fiber content. The preparations of samples were carried out by using the static pressure method. The diameter and height of sample was respectively 68.1mm and 20mm.
The SDJ-IItype three-speed electric strain direct shear instrument was used to test. The controlling loading rate was 0.8mm/min for shearing, and the test last for3-5minutes, and 0.01mm dial indicator was used to control shear displacement measurement accuracy. Every group of the shear test took four of the same specimens, which were under the vertical cutting pressure of 50, 100, 200, and 300kPa.

2.3 Experimental design

Previous trials (Tang et al., 2009) showed that the strength of fiber reinforced soil depended on the friction between fiber and soil particles mainly, so a Box-Behnken Design (BBD) was used to investigate the effects of 3 independent variables (porosity (X1), fiber content (X2) and fiber length (X3)) on the shear strength parameters. The independent variables were coded at three levels, and the complete design consisted of 17 experimental points carried out in a random order. The experimental design, including the uncoded and coded independent factors (Xi) and experimental levels, were showed in Table 3.

Table 3: Coded levels for 3 variables formed by BBD

Factors Codes	coded levels		
	-1	0	1
porosity	0.4	0.3	0.5
fiber content	1‰	3‰	5‰
fiber length	6	9	12

2.4 Statistical analysis

In RSM, the relationship between input variables and the resulting response value were explained by the following equation.Where the output response value y depended on the input variables x_1, x_2,…, x_i by the response surface f; and ε represented the statistical error.

$$y = f(x_1, x_2 \ldots x_i) + \varepsilon \tag{1}$$

According to the formula (1), the behavior of the system was represented by the following formula.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_{ii}^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j + \varepsilon \tag{2}$$

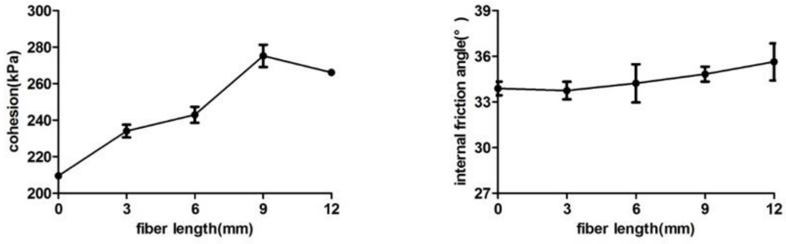
Where Y represented the shear strength parameters (Δc,$\Delta \Phi$) of 2 kinds of soil, β was the undetermined coefficients that were estimated by building response function with the commonest method to estimate β being the least square method, and β_0 was the constant; β_i(i=1,2,3) was the linear coefficient, β_{ii} was the quadratic coefficient of x_{ii}, β_{ij} was the coefficient of interaction effect. The accuracy of the response surface for the shear strength parameters could be analyzed by statistical analysis. ANOVA was used to evaluate the differences of test samples. According to the results obtained from the direct shear test, the test data was processed by ANOVA, and a fitting second-order regression model represented by formula (2) was constructed. Based on the obtained response surface equations, the optional conditions for fiber mixing were obtained.

3. Results and discussion

3.1 Single factor analysis

3.1.1 Fiber length

According to reference (Wu and Zhang, 2010), 3‰ fiber content PP fibers were selected as initial experimental materials. Direct shear strength test was conducted on fiber soil specimens with different fiber lengths (3mm, 6mm, 9mm and 12mm) and results were compared with the direct shear test results of plain soil. Shear strength parameters, after data processing, were shown in Fig. 1.



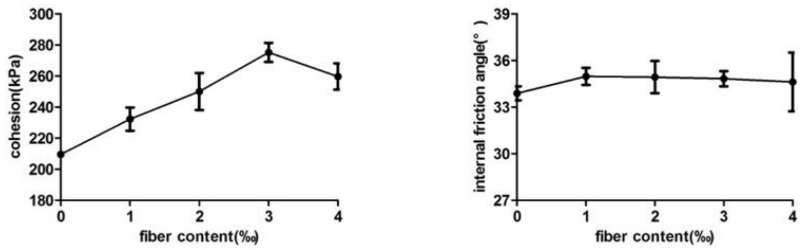
(a) Cohesion *(b) Internal friction angle*

Figure 1: Shear strength parameters of polypropylene fiber reinforced soil with different lengths

As shown in Fig. 1(a), there was a significant increase in the cohesion with increasing length of fiber from 3mm to 12mm, which peaked at a length of 9mm and then decreased. And it also could be seen from Fig. 1(b) that the internal friction angle of the fiber soil grew slowly with the increase of fiber strength. the 9mm fiber was selected as test materials.

3.1.2 Fiber content

According to above test results, 9mm was the best length to improve shear strength of clay. So 9mm was selected as the testing fiber length. Direct shear tests were conducted on fiber soil specimens with different fiber contents (0‰, 1‰, 2‰, 3‰, and 4‰). Shear strength parameters could be determined by the results of direct shear tests, and the results were shown in Fig. 2.

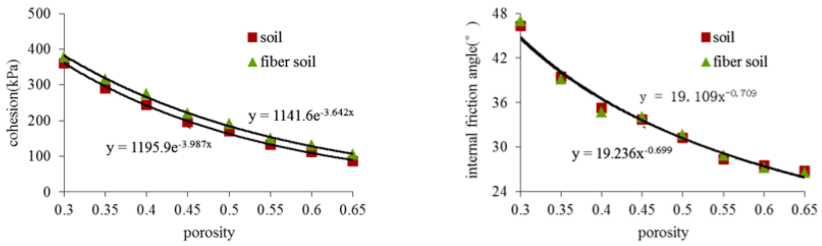


(a) Cohesion *(b) Internal friction angle*

Figure 2: Shear strength parameters of polypropylene fiber reinforced soil with different fiber contents

It could be seen from Fig. 3(a) that there was an obvious increment in cohesion along with the increase of fiber content up to 3‰ and then a decrease in cohesion was observed. And Fig. 2 showed that adding fiber would increase the cohesion, and the internal friction angle of fiber soil had little change with different contents. Part of the shear force was assumed by the soil itself in the process of shearing, and the others were transformed from the friction force between the soil particles and the fibers to the tensile force of the fibers. With the increment of fiber content, the distribution of fiber in soil increase, the total tensile strength of the fibers in the shear failure occurred, and the cohesion of the soil was greater.

3.1.3 Porosity



(a) Cohesion *(b) Internal friction angle*

Figure 3: Shear strength parameters of polypropylene fiber reinforced soil with different porosities

The soil density at different porosities (0.3%, 0.4%, 0.5%, and 0.6%) was calculated, and the corresponding quality of the soil and fiber (9mm, 3‰) was taken out for the shear test.
The trend of shear strength parameters of fiber soil and plain soil under different porosities was shown in Fig. 3. The cohesion of fiber soil and plain soil decreased exponentially with the increase of porosity, and cohesion of fiber soil was greater than that of plain soil; the internal friction angle of two soils decreased in the form of the power function, and the trend of internal friction angle of two soils under different porosities was almost coincident. With the increase of porosity, the reinforcement effect of the fiber on the cohesion of the soil increased at first and then decreased, and the fiber reinforcement effect was at its best when porosity was 0.4.

3.2 Response surface analysis

Combined with single factor test results, fiber content, fiber length and porosity were used as response factors, with 3‰, 9mm, 0.4 used as a center, a direct shear test was carried out according to BBD design. The results of cohesion differences were displayed in the last column in Table 4. The maximum cohesion difference was 50.4kPa in run 14, while the minimum cohesion difference was 0.28kPa in run 7.
Multiple regression analysis was used to analyze the cohesion differences from Table 4, and a quadratic polynomial equation was derived from regression analysis as follows:

Table 4: Results of BBD of response surface methodology

Std	Run	Factor 1 A:e	Factor 2 B:l mm	Factor 3 C:n ‰	Response Cohesion different kPa
16	1	0.40	9.00	3.00	39.07
1	2	0.30	6.00	3.00	15.25
12	3	0.40	12.00	5.00	20.39
2	4	0.50	6.00	3.00	20.72
8	5	0.50	9.00	5.00	19.39
11	6	0.40	6.00	5.00	15.03
4	7	0.50	12.00	3.00	22.28
15	8	0.40	9.00	3.00	38.89
6	9	0.50	9.00	1.00	14.02
3	10	0.30	12.00	3.00	25.19
14	11	0.40	9.00	3.00	40.1
5	12	0.30	9.00	1.00	14.81
7	13	0.30	9.00	5.00	14.68
13	14	0.40	9.00	3.00	40.4
9	15	0.40	6.00	1.00	12.66
17	16	0.40	9.00	3.00	38.14
10	17	0.40	12.00	1.00	21.23

Table 5: ANOVA for response surface quadratic model

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F
Model	1783.39	9	198.15	227.23	< 0.0001
A-e	5.25	1	5.25	6.02	0.0439
B-l	80.84	1	80.84	92.69	< 0.0001
C-s	5.73	1	5.73	6.57	0.0374
AB	17.56	1	17.56	20.13	0.0028
AC	7.56	1	7.56	8.67	0.0216
BC	2.58	1	2.58	2.95	0.1294
A^2	423.69	1	423.69	485.85	< 0.0001
B^2	299.13	1	299.13	343.02	< 0.0001
C^2	774.63	1	774.63	888.28	< 0.0001
Residual	6.1	7	0.87		
Lack of Fit	2.69	3	0.9	1.05	0.4621
Pure Error	3.41	4	0.85		
Cor Total	1789.49	16			

$$Y = 39.32 + 0.81x_1 + 3.18x_2 + 0.85x_3 - 2.1x_1x_2 + 1.38x_1x_3 - 0.8x_2x_3 - 10.03x_1^2 - 8.43x_2^2 - 13.56x_3^2 \quad \text{(in coded term)} \tag{3}$$

$$Y = -262.10 + 852.83x_2 + 21.11x_2 + 19.22x_3 - 6.98x_1x_2 + 6.86x_1x_3 - 0.134x_2x_3 - 1003.13x_1^2 - 0.94x_2^2 - 3.39x_3^2 \quad \text{(in actual factors)} \tag{4}$$

Where Y was the response variable (cohesion difference), x_1 was the coded value of porosity, x_2 was the coded value of fiber length, and x_3 was the coded value of fiber content.

From Table 5, the model F value of 227.23 with a low probability P value indicated high significance of the model. And the viscosity variation coefficient C.V% of cohesion was 3.11, so the coefficient of variation was small. A plot of experiment results versus the predicated value was showed in Fig. 4, actual test results and predicated values were very close, indicating high reliability of test results so that the tests could be analyzed by a model of two regression equation instead of the real point test. As a further check, the normality test of residuals was carried out (see Fig.5). It was obvious that all the test points were approximated in a straight line, and the results were distributed as the normal distribution.

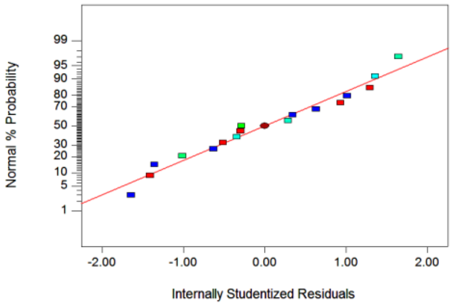


Figure 4: Normal plot of residuals for cohesion difference

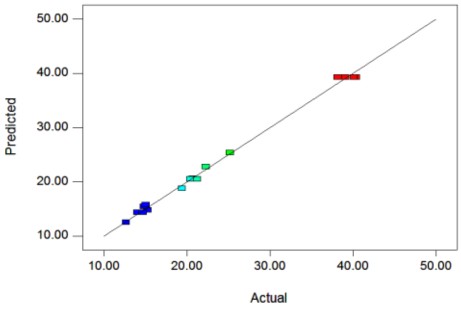


Figure 5: Plot of predicted values versus actual values of cohesion difference

According to the ANOVA results in Table 5, porosity, fiber length and fiber content were all significant factors that influence cohesion of fiber soil. And the result P(B)<P(A)<P(C) indicated that fiber length was the most important factor, followed by fiber content, and the significance of porosity was relatively small. P(BC) value was greater than 0.05, which indicated that interactions existed between porosity and fiber length, and between porosity and fiber content, whereas the interactions between fiber length and fiber content were not significant so that it could be ignored. Thus the final regression model could be simplified as follows:

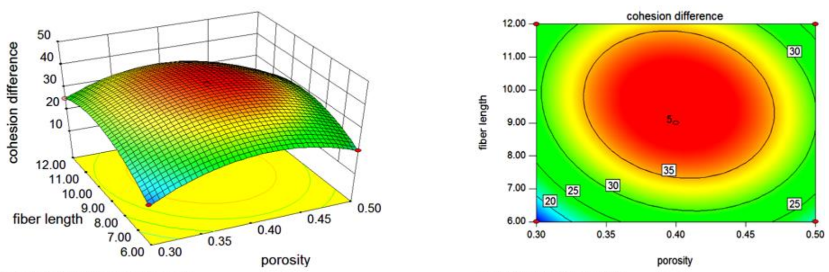
$$Y = 39.32 + 0.81x_1 + 3.18x_2 + 0.85x_3 - 2.1x_1x_2 + 1.38x_1x_3 - 10.03x_1^2 - 8.43x_2^2 - 13.5x_3^2 \quad (5)$$

According to the formula (6), Pareto analysis was performed to evaluate the effect weight of each factor on cohesion difference based on the following equation.

$$P_i = \left(\frac{\alpha_i^2}{\sum \alpha_i^2}\right) \times 100\% (i \neq 0) \quad (6)$$

Where P_i was the percentage of the effect weight of influence factor on cohesion difference, α_i was the coefficient of each variable in Formula (6).

It was obvious that cohesion difference was mainly affected by single factors, whose cumulative probability reached 98.31%. Among all factors, fiber content had the biggest influence that effected cohesion difference, whose probability reached 49.44%, accounting for half of the total contribution, followed by porosity and the fiber length. And the cumulative probability effect of interaction between porosity and fiber length and porosity and fiber content on cohesion difference was only 1.69% and could be ignored.



(a) 3D Surface Graph

(b) Contour Map

Figure 6: Surface and contour plots of mutual-influence for porosity and fiber length on cohesion difference

According to the ANOVA results, the interactions of x_1, x_2, x_1x_3 were significant, so the x_3 and x_2 were fixed at 0 level in the formula (5), and the response surface diagram and contour diagram of the interaction between porosity and fiber length and between porosity and fiber content were obtained (Fig.6).
It could be seen that the response surface of a different variable to cohesion difference was convex upwards at their tops, that was, with the increase of the single factor value, the cohesion difference showed the trend of increasing and then decreasing. The maximum value of cohesion difference was the highest point of the response surface. From Fig. 10, the results showed that the interaction between porosity and fiber length was significant when the fiber content was fixed at the same level.

4. Conclusion

The test carried out in this study contributes to the improvement of the soil shearing strength using the polypropylene fiber mixed soil. The single factor experiment showed that choosing appropriate fiber content, fiber length and porosity could effectively improve the effect of fiber reinforced soil on the shear strength. The change of the friction angle of the soil was not small, and the cohesion of the soil was mainly enhanced when adding fiber to soil. With the increase of fiber content, fiber length and porosity, the cohesion showed a trend of increasing and then decreasing. The best combination was a fiber content at 3%, fiber length at 9mm, and porosity at 0.4. A prediction model was established by RSM, the coefficient of determination (R^2) for cohesion difference models was found to be 0.9968. According to the analysis of variance of the regression equation obtained by the RSM, in response to the cohesion difference, three factors had a significant effect on the cohesion difference of the surface. In the three main factors that affect the cohesion difference, the influence order was fiber length, fiber content and porosity, and the interactions between and porosity and between fiber content and porosity were significant.

Acknowledgement

Supported by Fundamental Research Funds for the Central Universities (2572014CB21).

References

Butt W.A., Mir B.A., Jha J.N., 2016, Strength behavior of clayey soil reinforced with human hair as a natural fibre, Geotechnical & Geological Engineering, 34(1), 411-417, DOI: 10.1007/s10706-015-9953-x

Pradhan P.K., Kar R.K., Naik A., 2012, Effect of random inclusion of polypropylene fibers on strength characteristics of cohesive soil, Geotechnical & Geological Engineering, 30(1), 15-25, DOI: 10.1007/s10706-011-9445-6

Qu J., Sun Z., 2016, Strength behavior of shanghai clayey soil reinforced with wheat straw fibers, Geotechnical & Geological Engineering, 34(2), 515-527, DOI: 10.1007/s10706-015-9963-8

Shao W., Cetin B., Li Y., Li J., Li L., 2014, Experimental investigation of mechanical properties of sands reinforced with discrete randomly distributed fiber, Geotechnical & Geological Engineering, 32(4), 901-910, DOI: 10.1061/9780784480120.007

Tang C., Shi B., Gao W., Liu J., 2009, Single fiber pull-out test and the determination of critical fiber reinforcement length for fiber reinforced soil, Rock and Soil Mechanics, 30(8), 2225-2230.

Wu J.L., Zhang X.P., 2010, Polypropylene fiber reinforced expansive soil strength test, Soil Engineering and Foundation, 24(6), 71-76, DOI: 10.3969/j.issn.1004-3152.2010.06.021

Wu Y.K., Li Y.B., Niu B., 2015, Investigation of mechanical properties of randomly distributed sisal fibre reinforced soil, Material Research Innovations, 18(S2), 953-959, DOI: 10.1179/1432891714Z.000000000511

Yilmaz Y., 2015, Compaction and strength characteristics of fly ash and fiber amended clayey soil, Engineering Geology, 188, 168-177, DOI: 10.1016/j.enggeo.2015.01.018

Zaimoglu A.S., Yetimoglu T., 2012, Strength behavior of fine grained soil reinforced with randomly distributed polypropylene fibers, Geotechnical & Geological Engineering, 30(1), 197-203, DOI: 10.1007/s10706-011-9462-5