

Effect of basalt fiber inclusion on the mechanical properties and microstructure of cement-solidified kaolinite

D. Wang, H. Wang, S. Larsson, M. Benzerzour, W. Maherzi, Mouhamadou

Amar

► To cite this version:

D. Wang, H. Wang, S. Larsson, M. Benzerzour, W. Maherzi, et al.. Effect of basalt fiber inclusion on the mechanical properties and microstructure of cement-solidified kaolinite. Construction and Building Materials, 2020, 241, 10.1016/j.conbuildmat.2020.118085. hal-03224994

HAL Id: hal-03224994 https://hal.science/hal-03224994

Submitted on 21 Jul 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Version of Record: https://www.sciencedirect.com/science/article/pii/S0950061820300908 Manuscript_43988ce932d9882e7a2c3a1508d9d2b7

1	Effect of basalt fiber inclusion on the mechanical properties and				
2	microstructure of cement-solidified kaolinite				
3					
4	Dongxing WANG ^{a,c} , Hongwei WANG ^{a,b,*} , Stefan LARSSON ^c , Mahfoud				
5	BENZERZOUR ^b , Walid MAHERZI ^b , Mouhamadou AMAR ^b				
6					
7	a Key Laboratory of Geotechnical and Structural Engineering Safety of Hubei				
8	Province, School of Civil Engineering, Wuhan University, 430072 Wuhan, China.				
9	b Department of Civil Engineering and Environmental, IMT Lille Douai, EA 4515 -				
10	LGCgE, University of Lille, F-59000 Lille, France.				
11	c Department of Civil and Architectural Engineering, School of Architecture and the				
12	Built Environment, KTH Royal Institute of Technology SE-10044, Stockholm,				
13	Sweden.				
14					
15					
16					
17					
18					
19					
20					
21					
22					

Abstract: The polypropylene fibers, which are currently attracting enormous 23 attention in various geotechnical applications, carry a risk of aging under an 24 25 integrated effect of heat, oxygen, light and other environmental factors, causing potentially infrastructure failure. An eco-friendly and biologically inactive 26 material - basalt fiber, which has excellent natural resistance to aging and can 27 eliminate aging-associated disasters, deserves more attention in geotechnical field. 28 However, quite few studies are available on the beneficial reuse of basalt fibers to 29 improve the engineering performance of soils. Therefore, this study aims to 30 31 incorporate the sustainable basalt fiber and clarify how its inclusion impacts the mechanical properties and microstructure of cemented kaolinite. The experimental 32 programs are comprised of three types of tests, i.e. two to examine the compressive 33 34 strength and triaxial shear behavior and one to evaluate the microstructure properties. The results indicate that the basalt fiber reinforcement plays an essential role in 35 enhancing the compressive strength and peak deviatoric stress of cemented and 36 uncemented kaolinite. The inclusion of basalt fibers improves the ductility and 37 weakens the brittleness of cemented kaolinite. The compressive strength 38 increases with basalt fiber content and curing time, and reaches the peak at the 39 fiber content of 0.2 %, followed by a reduction due to the formation of weak zone 40 at higher fiber content. The peak deviatoric stress is elevated until reaching the 41 maximum at the basalt fiber content of 0.4 %, after which further addition of basalt 42 fiber tends to reduce its reinforcing effect. The peak deviatoric stress increases as the 43 basalt fiber length is shortened and the confining pressure is raised. The strength 44

gain of cement-basalt fiber inclusion is much more than the sum of strength 45 increase induced by them individually. The combination of basalt fiber and 46 47 cement has the virtues of both cement-stabilized and basalt fiber-reinforced kaolinite. The SEM analysis reveals that the mechanical interaction in the form of 48 49 interface bonding and friction between kaolinite particle, cement hydration product and basalt fiber is the dominant mechanism controlling the reinforcement-cementation 50 benefits. The bridging effect (reinforcement) of basalt fibers and binding effect 51 52 (cementation) of hydration products make a major contribution to the formation 53 of stable and interconnected microstructure, which results in an evident improvement in the mechanical behaviour of cemented kaolinite. The combination of 54 basalt fiber and cement stabilization would be an innovative and effective 55 56 method for geotechnical engineering works such as soft ground improvement.

57 Keywords: Basalt fiber; cemented kaolinite; compressive strength; peak deviatoric
58 stress; micro-mechanisms

59

60 **1 Introduction**

In the east-coastal area of China, soft clay is widely distributed and commonly encountered, which is the composition of clayey sedimentary or river flushing [1]. Over recent years, along with boost economic development and rapid population growth, a huge amount of construction engineering projects such as highway, land reclamation, airport, offshore wind power and sea-crossing bridge have to be built on soft clay grounds. However, the engineering performance of soft clay is worrying and

troublesome, principally because of its high water content, high compressibility, low 67 permeability and low bearing capacity. Fortunately, the detrimental effect of soft clay 68 69 can be effectively overcome by cement/lime solidification process, which is a cost-competitive and efficient route. Hence, cement/lime stabilization technology is 70 71 becoming more and more popular for soft clay improvement all over the world. It is well known that the cementitious materials such as cement, lime, Class F fly ash, 72 Class C fly ash, lime kiln dust and fiber as reported in [2-11] have been incorporated 73 in soil stabilization. 74

75 Currently, the fiber as a promising reinforcing material is commonly employed to reinforce cement/lime-treated soft clay in civil engineering practices. Many studies 76 77 through a number of triaxial compression (TC), unconfined compressive strength 78 (UCS), bearing capacity and direct shear tests have already been conducted to elucidate the effect of fiber reinforcement on cement/lime-treated soft clay. Wang et al. 79 [11] investigated the coupling effect of wheat straw fiber and lime, and even a small 80 amount of wheat straw fibers could improve their intensity of the strain-softening 81 behavior associated with lime stabilization. Tang et al. [12] found that the randomly 82 distributed polypropylene fibers significantly improve the tensile behavior and peak 83 strength of soils and reduce soil cracking. Ammar et al. [13] showed that the interface 84 shear strength parameters of natural hemp fiber-clay are largely affected by the testing 85 mechanisms and drainage conditions based on the interface direct shear and single 86 fiber pullout tests. Wang et al. [14] developed a useful modeling approach to predict 87 the pre-failure and failure behavior of fiber-reinforced clay subjected to TC tests, and 88

the predicted behavior was proved to have a good agreement with the experimental 89 response. The above-stated researches have shown that the fiber can be considered as 90 91 a good earth reinforcement material, which induces greater strength, roughness and 92 ductility and smaller post-peak strength loss, as compared to soil alone. However, the 93 fibers used in these studies are mostly polypropylene fibers, and only a few works [15,16] focusing principally on the dynamic properties have ever attempted to 94 introduce basalt fiber in soil reinforcement. Until now, the triaxial and uniaxial 95 compression behavior of basalt fiber-reinforced cemented soil 96 and 97 microstructural interaction between basalt fiber and cemented soil matrix which deserve to be further investigated are rarely reported. 98

In recent years, the basalt fiber owning to its sustainability and environmentally 99 100 friendly property has already been proved to be a good substitute for other fiber materials in geotechnical engineering. As a green and environmentally friendly fiber 101 that attracts very little attention until now, it uses natural basalt ore as raw material 102 and the major ingredients are SiO₂, Al₂O₃, FeO and Fe₂O₃. Especially, it is a typical 103 silicate fiber, which has a good natural compatibility (non-hazardous, biologically 104 inactive) with cement composite, excellent mechanical property, high temperature and 105 acid and alkali resistance. The mechanical property of basalt fiber is largely higher 106 than that of polypropylene fiber, but its price is only 1/10 of conventional carbon fiber 107 [17,18]. It has been widely used as the insulation, sound absorption and heat-resistant 108 materials to modify concrete [19-23]. However, the above literature reveals that the 109 application of basalt fiber to the soil reinforcement is indeed rarely reported until now 110

and the relevant studies are really lacking in the mechanical and microstructural properties of basalt fiber-reinforced soils. As a result, more attentions should be given on the performance and mechanism of basalt fiber to reinforce soft clay, especially in terms of basalt fiber reinforcement in cemented clay.

115 Therefore, the objective of this study is to better understand the effect of basalt fiber inclusion on the mechanical behavior of cemented kaolinite and identify the 116 corresponding microstructural mechanisms. In order to clearly investigate the 117 influence of several factors including basalt fiber content, fiber length, curing time 118 119 and confining pressure σ_3 , a series of UCS and consolidated-undrained (CU) TC tests are carried out on cemented kaolinite. The interfacial interaction between basalt fibers, 120 121 cement hydration products and kaolinite particles and the relevant microstructure of 122 fiber-reinforced cemented kaolinite are deeply discussed by conducting scanning electron microscopy (SEM) tests, to obtain a preliminary knowledge of the intrinsic 123 mechanisms of basalt fiber inclusion. The final purpose of this study is to propose a 124 125 novel combination of basalt fiber with cement, which can provide some reference for soft ground improvement. 126

- 127 **2 Materials and methods**
- 128 **2.1 Materials**

Kaolinite (abbreviated to K) with grey color was obtained from a kaolinite manufacturer Co. LTD in Yidu city in China, since it is easily obtained in practice. As shown in Table 1, the basic physical characteristics of tested kaolinite were determined in laboratory according to *the standard test methods of soils for highway* *engineering defined by JTG E40-2007* [24]. The initial water content of kaolinite is 0.17 %. The specific gravity is 2.75 determined by the pycnometer test. The liquid limit and plastic limit are, respectively, 31.0 % and 20.1 %, measured by the liquid-plastic limit combined test method. Thus, the plasticity index value of this kaolinite material is 10.9 %, which shows a low compressibility. The modified Proctor compaction test provides an optimum water content of 22.4 % and maximum dry density of 1.62 g/cm³ for the tested kaolinite.

The cement used in this study is P.O 42.5 ordinary Portland cement (P), and its 140 141 chemical compositions are listed in Table 2. The basalt fibers (B), as presented in Fig. 1, have the length of monofilament of 3 mm, 7 mm and 11 mm. The technical 142 specifications of the chosen basalt fibers are summarized in Table 3. The basalt fiber 143 has a density of 2.63 g/cm³, which is similar to the maximum dry density of kaolinite. 144 The parameters of monofilament are 7-15 µm in diameter, 1050 °C in melting point, 145 tensile strength of 3000-4800 MPa and modulus of elasticity of 91-110 GPa. The 146 above-mentioned data indicate that the basalt fiber has excellent mechanical property, 147 corrosion resistance and acid and alkali resistance. 148

149 **2.2 Sample preparation and test methods**

150 **2.2.1 Unconfined compressive strength test**

The mixture design formulations for investigating the effect of basalt fiber on cemented kaolinite are reported in Table 4, where the abbreviation of KxPyB-z represents the kaolinite samples solidified with x % cement and y % basalt fiber with length of z mm. All the tested samples were prepared under the conditions of optimum

moisture content and maximum dry density determined by the modified Proctor 155 compaction tests. To control the economic cost and avoid the fiber agglomeration 156 during mixing, the used basalt fiber contents were 0, 0.1 %, 0.2 %, 0.3 % and 0.4 % 157 for UCS tests, calculated on the dry mass of kaolinite, while the cement content was 158 159 fixed at 6 % of dry kaolinite weight. It is noteworthy that the basalt fiber contents are chosen based on previous studies [12,17,25] and 6% cement is fixed since it 160 was proved as an economic and reasonable amount to improve the engineering 161 property of soil according to [26]. First, the distilled water and kaolinite were mixed 162 163 by a mechanical mixer until the optimum water content of 22.4 % was reached, and afterwards stored in an airtight container for 24 h to achieve an internal uniform 164 moisture distribution. Second, the basalt fibers and cement were simultaneously added 165 166 in the prepared moist kaolinites and mixed together for 10 mins by a laboratory mechanical mixer, and a visual examination was performed to ensure the homogeneity 167 of mixture. Finally, the prepared mixture was put into a cylindrical mould of 50 mm in 168 169 diameter and 50 mm in height, and later compacted and demolded through a hydraulic jack. The demolded cylindrical samples were immediately sealed with plastic film, 170 and cured at constant temperature of 20 ± 2 °C and relative humidity of 95 ± 2 % for 3 171 d, 7 d, 14 d, and 28 d. The UCS tests were performed with a universal testing machine, 172 and the vertical loading was applied to the sample at a constant displacement rate of 1 173 mm/min until failure. Three samples were tested for each mixture and the average 174 value was calculated to determine the compressive strength. Note that all the tests 175 were extended to the basalt fiber-reinforced kaolinite (Group 1) as reference, to make 176

a comparison between basalt fiber-reinforced uncemented kaolinite (BFUK) and
basalt fiber-reinforced cemented kaolinite (BFCK) (Group 2).

179 **2.2.2 Undrained triaxial compression test**

A similar approach was employed in triaxial tests to prepare samples in the cylindrical 180 181 moulds with 39.1 mm in diameter and 80 mm in height according to the standard test methods of soils for highway engineering defined by JTG E40-2007 [24]. As 182 shown in Table 4, the designed samples for triaxial tests are kaolinite samples 183 solidified with constant cement content of 6 % and different amounts of basalt fibers 184 185 with different lengths. Thereafter, Group 3 was developed to investigate the effect of basalt fiber inclusion on the triaxial shear behavior of cemented kaolinite. The basalt 186 fiber contents chosen in Group 3 are 0, 0.1 %, 0.2 %, 0.3 %, 0.4 % and 0.5 % by 187 188 weight of dry kaolinite powder, and the basalt fiber length is a constant of 11 mm in this case. To investigate the impact of basalt fiber length, Group 4 was designed given 189 that the fiber lengths are 3 mm, 7 mm and 11 mm and the basalt fiber contents are 190 settled at 0.2 % by weight of dry kaolinite. By using a static compaction method, each 191 sample for triaxial tests was compacted in three layers to ensure a uniform compaction 192 degree. Once the sample preparation was completed, the samples were sealed with 193 hermetical plastic film and cured at room temperature of 20 ± 2 °C and relative 194 humidity of $95 \pm 2\%$ for 7 d. After that, the consolidated undrained (CU) triaxial tests 195 were carried out according to Chinese standard JTG E40-2007 [24], and each of the 196 samples was tested at three different confining pressures of 50 kPa, 100 kPa and 200 197 kPa at constant vertical strain rate of 0.1 mm/min. During the loading process, the 198

199 deviatoric stress $q = \sigma_1 - \sigma_3$ was recorded as a function of axial strain ε until the 200 post-failure regime, and the maximum ε that was permitted to occur in triaxial tests 201 was 5 %. Especially, the whole shearing process was automatically controlled by a 202 specialized computer to realize a real-time acquisition of test data.

203 **2.2.3 SEM test for morphological analysis**

The representative specimens after unconfined compression tests were chosen for the 204 detailed microstructural characterization of cement-fiber solidified kaolinites by using 205 scanning electron microscopy. The selected specimens were dried in an oven at 40 °C 206 until they attained constant weight, and then the blocks of a size of about 1 cm³ were 207 prepared. The scanning electron microscopy specimens should be first gold-coated by 208 a sputtering technique to make them conductive and avoid charging effect. Finally, the 209 210 associated internal changes in the microstructure of cement-treated specimens owning to the basalt fiber inclusion were identified through SEM analysis on FEI Quanta 200 211 machine. 212

213 **3 Results and Discussion**

3.1 Unconfined compressive strength behavior

215 3.1.1 Stress-strain relationship

216 The stress-strain curves of BFUK and BFCK defined by UCS tests are shown in Fig.

217 2, where all the samples were prepared at varying basalt fiber contents and cured for

- 218 28 d. It can be seen from Fig. 2 (a) that for BFUK without fiber (K0B), the vertical
- 219 stress σ_1 increases until its peak of 0.21 MPa corresponding to the failure strain ε_f of
- 220 3.2 % as the axial strain ε extends, followed by a sharp decrease in stress. The ε_f

values of BFCK with 0.1 %, 0.2 %, 0.3 % and 0.4 % basalt fibers are respectively
3.2 %, 3.6 %, 3.6 % and 4.3 %, while the corresponding peak stress is 0.20 MPa, 0.25
MPa, 0.24 MPa and 0.20 MPa. Compared with K0B, it is evident that the peak stress
decreases slightly at the basalt fiber content of 0.1 % (K0.1B-3) and 0.4 % (K0.4B-3),
and then goes up if the basalt fiber content changes to 0.2 % (K0.2B-3) and 0.3 %
(K0.3B-3).

Fig. 2 (b) describes the variation of stress-strain curves of BFCK samples with various 227 228 basalt fiber contents at 28 d. Upon comparison with Fig. 2 (a), it can be seen that the 229 peak axial stress σ significantly increases owing to the addition of 6 % cement and the maximum peak stress appears for BFCK sample with 0.2 % of basalt fiber 230 (K6P0.2B-3). The σ is initially elevated with an increase in ε until the peak stress is 231 232 reached, and then the σ decreases sharply as the ε continues to rise. Owing to the effect of cement stabilization, the ε_f of BFCK with 0.1 %, 0.2 %, 0.3 % and 0.4 % 233 basalt fibers are 3.1 %, 3.4 %, 3.5 % and 3.3 %, respectively, and the peak stress is 234 correspondingly 5.49 MPa, 6.56 MPa, 5.72 MPa and 5.48 MPa. 235

Especially, both the BFUK and BFCK samples reinforced with basalt fiber exhibit a more ductile behavior since the failure strain ε_f is more or less raised due to the effect of fiber inclusion. This finding accords well with the previous studies reported in [11,12,15]. Furthermore, the post-peak stress level of BFCK samples is intensified owing to the addition of basalt fiber under the same ε . It is undoubted that one of the main advantages related to the reinforcement effect of basalt fiber when applied to kaolinite is the improvement in material ductility.

Especially, from the typical stress-strain curves such as BFUK (K0.2B-3) and BFCK 243 (K6P0.2B-3), it can be concluded that the curves can be divided into four stages: (i) 244 245 initial compaction stage: the fine particles rearrange and orientate themselves under very low vertical loading, diminishing the interparticle pore volume; (ii) elastic 246 247 deformation stage: the σ approximately increases linearly when the ε increases; (iii) plastic deformation stage: the σ has a relatively slow growing trend with increasing ε 248 before the σ reaches its peak; (iv) post-failure stage: once the σ exceeds the peak 249 strength, it starts to decreases sharply as the ε slightly increases. 250

3.1.2 Unconfined compressive strength

Fig. 3 (a) and (b) shows respectively the variation of UCS of BFUK and BFCK 252 samples with varying basalt fiber contents. For BFUK samples in Fig. 3(a), the 253 254 maximal UCS occurs at the curing time of 28 d, where the UCS decreases a little from 0.21 MPa (K0B) to 0.2 MPa (K0.1B), and then rises to 0.262 MPa with the increase 255 of basalt fiber content from 0 to 0.1 % and 0.2 %. However, further increase in basalt 256 fiber content from 0.2 % to 0.3 % and 0.4 % produces a downward trend of UCS, 257 being reduced correspondingly from 0.262 MPa to 0.256 MPa and 0.202 MPa. Hence, 258 259 it could be deemed that the suitable content of embedded basalt fiber for reinforcing BFUK samples is around 0.2 %, where the highest UCS is reached. For BFUK 260 samples with varying basalt fiber contents, their UCS tends to increase with curing 261 time from 3 d to 28 d, which might be due to the water evaporation from the surface 262 and inside of samples. The reduction in the water content of samples induces an 263 observable augmentation in the UCS with increasing curing time. 264

As shown in Fig. 3 (b), a slight decrease in UCS because of the inclusion of 0.1 %265 basalt fiber (K6P0.1B) is observed as compared to the sample without basalt fiber 266 267 (K6P0B), independent of curing time from 3 d to 28 d. The 28-day UCS of samples increases respectively by -1.90 %, 22.92 %, 10.11 % and 3.67 % with basalt fiber 268 content from 0.1 % to 0.4 %, as compared to cemented kaolinite without basalt fiber 269 (K6P0B). These analyses indicate that the suitable content of basalt fiber for 6 % 270 cement solidified samples is around 0.2 % according to the change of UCS. At the 271 basalt fiber content of 0.2 %, the UCS of fiber-reinforced cemented kaolinite at 7 d, 272 273 14 d and 28 d is respectively 5.20 MPa, 6.26 MPa and 6.55 MPa, increasing by 25.00 %, 50.48 % and 57.45 % as compared with the corresponding sample at 3 d 274 275 (4.16 MPa).

276 In addition, the UCS and strength increase of basalt fiber plus cement solidified samples in Fig. 3 (b) is far more significant than that generated singly by the basalt 277 fiber inclusion in Fig. 3 (a). Under the condition of 0, 0.1 %, 0.2 %, 0.3 % and 0.4 %278 basalt fiber inclusion, the 28-day strength of BFCK increases correspondingly by 279 25.87, 26.48, 24.02, 21.38 and 26.09 times as compared with the corresponding 280 BFUK samples. Especially, a combination of 0.2 % basalt fiber and 6% cement for 281 28-day kaolinite sample K6P0.2B produces a strength of 6.55 MPa, which is greater 282 than both the strength brought by 0.2 % basalt fiber (i.e. sample K0.2B, 0.262 MPa) 283 and the strength generated by 6 % cement (i.e. sample K6P0B, 5.64 MPa). 284 From the obtained results, it can be seen that the basalt fiber content and curing time 285

286 play an observable role in the UCS levels. The cementation effect from the cement

hydration is much more important than the reinforcing effect of basalt fiber for the UCS amelioration of kaolinite, which has been reported by Wang et al. [11]. The strength gain analysis indicates that the combined effect of basalt fiber and cement within soil matrix (i.e. interfacial mechanical interaction) is not a simple summation of their individual contribution, but is in fact a complex coupled effect on the strength improvement. This conclusion coincides well with the result obtained by Wang et al. [11].

3.2 Triaxial shear behavior

295 **3.2.1 Deviatoric stress versus axial strain**

296 The typical relationships of deviatoric stress q versus axial strain ε obtained by triaxial 297 compression (TC) tests are shown in Fig. 4, where BFCK sample exhibits an obvious strain-softening behavior. Fig. 4 (a) presents the q versus ε curves of BFCK samples 298 299 at varying basalt fiber contents and constant confining pressure σ_3 of 100 kPa. The q- ϵ relationships of BFCK are discussed merely for σ_3 of 100 kPa due to the similarity of 300 the q- ε behavior between different σ_3 levels. It appears that the basalt fiber inclusion 301 contributes to an improvement in the peak deviatoric stress qp of cement-treated 302 kaolinite samples. The magnitude of this contribution, which varies depending on the 303 304 basalt fiber content, tends to increase with increasing basalt fiber content from 0.1 %to 0.4 % and afterwards decreases slightly in case of further elevating the fiber content 305 to 0.5 %. 306

The q- ε curves obtained from TC tests are given in Fig. 4 (b) for BFCK samples with varying basalt fiber lengths and at σ_3 of 100 kPa. It can be seen from Fig. 4 (b) that the q_p of BFCK samples with 0.2 % basalt fiber significantly increases with basalt fiber length reduced from 11 mm to 3 mm, and the maximum q_p occurs at the fiber length of 3 mm. As reported in Fig. 4 (c), three different levels of σ_3 including 50 kPa, 100 kPa and 200 kPa were employed to evaluate the q- ε curves of samples K6P0.2B-11 and K6P0B. As expected, the results demonstrate that the q_p of BFCK can be greatly improved as σ_3 goes up from 50 kPa to 200 kPa.

315 Therefore, the above-mentioned results reveal that these factors including basalt fiber content, basalt fiber length and confining pressure level could have an important 316 317 impact on the q- ε behavior of fiber-cement reinforced sample. The optimal basalt fiber content to ameliorate the q- ε behavior of BFCK can be approximately 318 319 considered as 0.4 %, which is evidently different from the optimal basalt fiber content estimated by UCS tests. Compared to long basalt fibers, shorter discrete fiber mixed 320 uniformly within the soil mass can increase the number of fibers in a unit volume of 321 322 soil mass, and the acquired reinforcement benefit of basalt fiber to UCS is therefore 323 more pronounced. The lateral deformation of tested samples could be further prevented at higher confining pressure, which enhances to a certain extent the UCS 324 325 levels.

326 **3.2.2 Variation of peak deviatoric stress**

It is obvious to know from Fig. 4 that BFCK samples exhibit strain-softening behavior. Figures 5-7 show the variation of q_p and peak stress ratio R_f of BFCK with basalt fiber content, basalt fiber length and confining pressure. The peak stress ratio R_f is defined as the ratio of peak deviatoric stress q_{pr} of reinforced samples to that of unreinforced samples (without fiber) q_{p0} [27].

$$R_f = \frac{q_{pr}}{q_{p0}}$$

Fig. 5 shows the effect of varying basalt fiber contents (0, 0.1 %, 0.2 %, 0.3 %, 0.4 % and 0.5 %) on the q_p and R_f of BFCK samples. For instance, at the σ_3 of 100 kPa, the q of cemented kaolinite sample without basalt fiber (K6P0B) is 2.11 MPa, while the addition of 0.1 %, 0.2 %, 0.3 %, 0.4 % and 0.5 % basalt fiber results in an increase of q to 2.64 MPa (K6P0.1B), 2.82 MPa (K6P0.2B), 3.36 MPa (K6P0.3B), 3.62 MPa (K6P0.4B) and 3.40 MPa (K6P0.5B). The R_f correspondingly increases from 1.0 (K6P0B) to 1.25 (K6P0.1B), 1.33 (K6P0.2B), 1.59 (K6P0.3B), 1.71 (K6P0.4B) and 1.61 (K6P0.5B).

341 The results reveal that the addition of basalt fiber as reinforcing materials provides an approach to enhance the q_p of cemented kaolinite, and the percentage of basalt fiber 342 343 plays a significant role in improving the qp of BFCK. Especially, qp of cemented kaolinite reaches the optimum level at 0.4 % of basalt fiber when compared with other 344 basalt fiber contents, and higher or lower amount of basalt fiber would bring about a 345 346 decrease in the q_p of basalt fiber-cement solidified kaolinite samples. It is interesting 347 to note that a similar trend can be observed for the change of Rf ratio with basalt fiber content. Rf tends to increase continuously with basalt fiber content, and the maximum 348 349 ratio occurs also at 0.4 % of basalt fiber, being independent of σ_3 levels.

Fig. 6 shows the effect of varying basalt fiber lengths (0, 3 mm, 7 mm and 11 mm) on 350 the q_p and R_f of BFCK. For a specific percentage of 0.2, it can be observed that the 351 introduction of basalt fiber with length of 3 mm, 7 mm and 11 mm improves greatly 352 353 the q_p of cemented kaolinite compared to the control sample - cemented kaolinite 354 without basalt fiber (i.e. K6P0B, 2.59 MPa). The qp value reaches up to 4.52 MPa, 3.65 MPa and 3.40 MPa after adding 0.2 % basalt fiber with length of 3 mm, 7 mm 355 and 11 mm respectively, while the corresponding R_f changes from 1.0 to 1.45, 1.33 356 and 1.31. Similar to the strength variation with basalt fiber content, the q_p and R_f has a 357 rising trend with fiber length until their individual peak, followed by an observable 358 359 reduction as a result of further prolongation of fiber length. The analysis indicates that the basalt fiber length exerts a significant impact on the q_p of samples, and shorter fiber length of 3 mm is proved to be more effective than longer fibers of 7 mm and 11 mm in enhancing the triaxial shear behavior of cemented kaolinite. This finding is in good agreement with that reported by Prabakar et al. [27], and the relevant microstructural mechanisms will be discussed as follows.

In order to study the effect of σ_3 levels, the mechanical properties of BFCK samples defined by triaxial tests are reported in Fig. 7, which shows the q_p evolution of cement-fiber treated samples under three different σ_3 . The q_p values of K6P0.2B-3 sample at σ_3 of 50 kPa, 100 kPa and 200 kPa are respectively 3.15 MPa, 3.71 MPa and 4.52 MPa, which are evidently higher than that of other samples.

For cement-fiber solidified samples, the q_p has an increasing trend with growing σ_3 , but R_f presents differently a decreasing tendency. It is potentially because that the cemented kaolinite remains relatively loose under lower σ_3 and a large number of tiny pores may exist inside the samples. Owing to the augmentation in σ_3 , the diminution in pore size and pore volume inside kaolinite samples takes place by expulsion of free water, and the biting force between basalt fibers and kaolinite particles increases, enhancing the basalt fiber reinforcement and sample stiffness.

377 **3.3 Microstructure**

378 **3.3.1** Micro-mechanisms related to basalt fiber inclusion

To understand the macroscopic behavior of basalt fiber-reinforced kaolinite, the microstructural observation should be performed by SEM **tests** and the results are shown in Figures 8-10. Fig. 8 (a) gives the SEM image of BFUK typical specimen with basalt fiber content of 0.2 % after being subjected to UCS tests. The shape and location of basalt fiber could be clearly identified, appearing inside the typical

specimen of uncemented kaolinite. In the local marked magnified area in Fig. 8 (b), it 384 is easier to detect that the basalt fiber surface is attached by many kaolinite minerals, 385 386 which is indicative of a good bonding between kaolinite particles and basalt fibers. Due to the firmly reinforced interaction between basalt fibers and kaolinite particles, 387 388 they are capable of jointly bearing the external loadings [28], and the interfacial force between kaolinite particles and basalt fibers increases gradually to resist the external 389 loading imposed on BFUK samples [29]. In this case, the surface roughness of fiber 390 plays an important role in ameliorating the interface friction between fiber and 391 392 kaolinite particles, improving the resistance to the external loading.

Fig. 8 (c) shows the SEM image of typical specimen BFCK solidified with 6 % 393 cement plus 0.2 % basalt fiber. The surface of basalt fiber is widely attached by the 394 395 hydration products (ettringite AFt and C-S-H gels) of cement and less kaolinite minerals in comparison with the SEM image presented in Fig. 8 (a). It is well known 396 that the main hydration products (C-S-H gels, AFt etc.) can greatly improve the 397 strength performance by cementing fine grains and filling pore spaces [1-8]. This 398 helps to improve the physical bonding strength of kaolinite particles and enhance the 399 adhesion of basalt fiber with cemented soil matrix. 400

Fig. 8 (d) shows the local marked magnified area as outlined in Fig. 8 (c). It is clear that the hydration products including fine fibrillar C-S-H gels (they might grow gradually into reticulate or honeycomb-like network as reaction proceeds) and rod-like AFt crystals are wrapped tightly around cement grains and effectively restricts the relative movement between basalt fibers and cemented aggregates

(especially at cement-fibre interface). To firmly support the SEM analysis on 406 cement-fiber solidified soil, the EDX patterns of C-S-H gels and Aft are shown in 407 Figure 8 (e)-(f). The rod-like structure found at some locations in Figure 8(e) 408 contains calcium, silica, oxygen and significant amount of sulfur and can be 409 410 labeled as Aft, and this finding agrees well with Li et al. [30]. The gel-like structure marked in Figure 8(f) reveals the presence of calcium, silica and oxygen 411 in high concentrations and could be confirmed as C-S-H gels (gelled aggregates 412 contained potentially Aft and fine soil), and this conclusion has a good agreement 413 414 with Alawad et al. [31]. Therefore, this contributes significantly to the solidification benefit brought by the coupling effect of basalt fiber inclusion and cementitious 415 hydration products, and the strength of BFCK is reasonably much higher than that of 416 417 BFUK. This is the main reason why the combination of basalt fiber and cement hydration seems to be more efficient and attractive in improving the strength behavior 418 than the single addition of basalt fiber or cement alone. 419

420 **3.3.2 Identification of fiber distribution mode and interface friction**

Fig. 9 shows the distribution modes of basalt fibers embedded within the BFCK specimens at 200 times magnification. It is obvious that the randomly distributed basalt fibers in these specimens act similarly to the plant roots, and meanwhile, the high binding ability of hydration products attached on the fiber surface toughens the randomly distributed fibers as well, distributing the applied stresses in a broader area and inhibiting further the fissure propagation. According to the SEM micrograph in Fig. 9 (a), it can be clearly seen that a few basalt fibers are tightly surrounded by

kaolinite particles within BFCK specimen with 0.1 % basalt fiber. For the SEM 428 micrograph of BFCK with 0.2 % basalt fiber in Fig. 9 (b), the surface of basalt fiber is 429 430 attached by cement hydration products and kaolinite matrix, strengthening the interfacial interaction between fiber, cement and kaolinite. Accordingly, the basalt 431 432 fibers, cement hydration products and kaolinite particles contribute jointly to the formation of a stable and interconnected structure inside the specimens through the 433 combined action of cementation, pore filling and bridging. When the samples are 434 subjected to external loading, the bridging effect of fibers and cementation effect of 435 436 hydration products can efficiently impede the further development of tension cracks and the loading-related deformation of kaolinite samples. As a result, the basalt 437 fiber-reinforced cemented kaolinite demonstrates in Fig. 2 (b) a somewhat stronger 438 439 ductile behavior. This provides a reasonable explanation for the notable change in the brittleness-ductility characteristics (i.e. stress-strain behavior) of cement-fiber 440 reinforced kaolinite samples. 441

Owning to the further addition of basalt fiber, more basalt fibers per unit section can 442 be identified in the SEM micrograph of BFCK specimen with 0.3 % basalt fiber in Fig. 443 9 (c), where the basalt fibers are non-uniformly distributed. This can result in a more 444 intensified mechanical interaction between basalt fibers inside the specimens and also 445 the potential formation of weak surface. Note that the phenomenon of fiber 446 agglomeration may occur in the case of non-uniformly mixed matrix. As a result, the 447 basalt fiber may slide out of the cemented kaolinite specimen when subjected to 448 external loading and the sliding failure occurs most probably along the weak surface. 449

Therefore, the presumable reason for the UCS decrease of sample with 0.3 % basalt 450 fiber is closely related to the non-uniform distribution of basalt fibers, which have 451 452 also been mentioned by Ma and Gao [15] and Ahmad and Chen [32]. This may be the dominant reason why further inclusion of basalt fiber beyond its optimum amount 453 454 brings about a drop in the compressive strength and shear resistance of fiber-cement solidified specimens. Hence, it can be proposed that the strength improvement of 455 BFCK samples depends principally on three factors: (i) tensile strength of basalt fiber, 456 (ii) surface roughness of basalt fiber and bonding behavior of cemented kaolinite and 457 458 (iii) distribution and size of basalt fiber in cemented kaolinite. The cementitious hydration products of cement and reinforcement of basalt fibers create altogether a 459 better bridging property, reinforce the interlocking of cemented aggregates and fill in 460 461 pore spaces within cemented kaolinite, which without doubt leads to superior strength performance than cemented kaolinite without basalt fiber. 462

As presented in Fig. 10, the experimental evidence is captured to identify the interface 463 464 friction between basalt fiber and kaolinite. Fig. 10 (a) shows the pullout behavior of basalt fibers, in which a scratch trace is formed on the specimen section and the 465 failure mechanism of BFCK is revealed. When the specimen is subjected to external 466 loading, the basalt fibers with excellent tensile strength can further prevent the 467 extension of cracks and prolongation of fractures, until they are pulled out of kaolinite 468 specimens. The interface friction between fiber and cemented particles, which is 469 closely related to the surface roughness of basalt fiber, provides a strong pullout 470 resistance to the tensile traction transformed from external loading. As shown in Fig. 471

10 (b), the scratch trace at the ends of basalt fibers can also be observed, and this may 472 be predominantly the original section formed during the fiber production process or 473 474 caused by the friction between basalt fibers and hard particles. In Fig. 8 and Fig. 9, it is apparent that most of the basalt fibers are naturally stretched due to its excellent 475 476 mechanical performance and the surface has no evident deformation or scratch. This is different from the phenomenon of a lot of scratches squeezed on the surface of 477 polypropylene fibers in the marked area of Fig. 10 (c), because the basalt fiber has 478 much more excellent mechanical resistance to deformation than the polypropylene 479 480 fiber.

481 **3.3.3 Schematic illustration of fiber-cement-kaolinite system**

482 The mechanical strength of cement-stabilized soils are greatly influenced by several 483 factors such as cement content, curing time and water to cement ratio [1,5,6,33,34], which are tightly associated with a series of physic-chemical reactions including 484 cation exchange, flocculation, hydration and potential pozzolanic reactions between 485 486 cement and moist soils. The chemical reactions can generate new cementitious phases, such as C-S-H gels and ettringite etc., as detected in SEM images, and promote the 487 structural integrity and mechanical behavior of cemented kaolinites by physical 488 bonding and pore-filling. The incorporation of basalt fiber into kaolinite matrix can 489 produce a reinforcement effect, which would affect the stiffness, failure strain and 490 compressive strength of stabilized kaolinites [11,12,25,28]. The bridging benefit of 491 basalt fiber could intensify the interfacial interaction between basalt fiber and 492 kaolinite particle, including interface cohesion and interface interaction. This can 493

494 effectively improve the resistance of kaolinite to deformation and limit the
495 development of micro-cracks within samples. Especially, shorter basalt fiber increases
496 the contact area and interface force between fiber and kaolinite, thereby improving the
497 net-like interconnected structure and the mechanical performance of cement-fiber
498 stabilized kaolinite.

According to the above-stated SEM analysis, Figure 11 summarizes the interfacial 499 mechanical behavior of kaolinite stabilized with cement-basalt fiber. It can be found 500 that the mechanical interaction between basalt fibers, cement hydration products 501 502 (C-S-H gels, AFt etc.) and clay particles is mainly composed by three forces originating from different sources: (i) the hydration products of cement can effectively 503 bond clay particles and basalt fibers together, leading to the formation of a 504 505 well-interconnected and stable skeletal structure; (ii) the adhesive force is the main force between basalt fibers and kaolinite particles since the kaolinite is mainly 506 composed of fine particles; and (iii) certain amount of kaolinite particles are attached 507 on the rough surface and edge of basalt fibers, which would produce the 508 non-negligible biting force and interface fiction to restrict the deformation and relative 509 movement when the samples are subjected to external loading. Especially, a small 510 amount of carbonates might unexpectedly emerge in certain cases owning to the 511 carbonation of reactive binder after exposure to CO₂ in air during the mixture 512 preparation and standard curing of samples, and the carbonation reactions and 513 corresponding products have been systematically discussed by Wang et al. [35-38]. 514

515 4 Conclusions

23

As an eco-friendly and biologically inactive material that until now attracts very little attention, the combination of basalt fiber with cement has been proposed as an efficient and cost-effective method to treat soft clays in ground engineering. This study highlights the effect of basalt fiber inclusion on the mechanical properties and microscopic mechanisms of kaolinite through a series of UCS, TC and SEM tests. The main conclusions drawn from the obtained data are summarized as follows.

(i) The basalt fiber reinforcement combined with cement stabilization is demonstrated to be effective for the improvement in the compressive strength and shear resistance of kaolinite. However, the single presence of basalt fiber plays a minor influence on the compressive strength in comparison with the combination of basalt fiber and cement, which has the virtues of both basalt fiber-reinforced kaolinite and cement-stabilized kaolinite.

(ii) The inclusion of basalt fiber can improve the ductility behavior and post-peak strength of cemented kaolinite owing to the bridging effect. It exists an optimum basalt fiber content of 0.2 % where the UCS reaches its peak, and higher or lower content of basalt fiber causes strength degradation rather than an improvement.

(iii) The peak deviatoric stress defined by triaxial tests have an increasing trend until
an optimum basalt fiber content of 0.4 %, after which further increase in fiber content
reduces the reinforcement effect due to its non-uniform distribution within samples.
Short fiber length of 3 mm is proved more effective in improving the peak deviatoric
stress of cemented kaolinite than longer fiber of 7 mm and 11 mm. The elevated
confining pressure results in a continuous improvement in the peak deviatoric stress.

(iv) The interfacial mechanical interaction between kaolinite, cement hydration product and basalt fiber contributes to the formation of a well-interconnected skeletal structure by the combination of fiber reinforcement and cement stabilization. This is the main reason why the inclusion of randomly distributed basalt fiber can greatly improve the mechanical performance of cemented kaolinite.

543

544 Acknowledgment

This work was supported by the National Natural Science Foundation of China (Grant
no. 51879202, no. 51609180).

547

548 **References**

- 549 [1] T. Deng, Y. Deng, X. Yue, Y. Cui, Deterioration of marine soft clay at east China
- solidified by cement-metakaolin composite, Environ. Geotech., (2019)
 https://doi.org/10.1680/jenge.18.00202.
- 552 [2] D. Wang, R. Zentar, N. E. Abriak, Durability and swelling of solidified/stabilized
- dredged marine soils with class F fly ash, cement and lime, J. Mater. Civil Eng. 30(3)

554 (2018) 04018013.

- 555 [3] D. Wang, R. Wang, M. Benzerzour, H. Wang, N.E. Abriak, Comparison between
- reactive MgO- and Na₂SO₄-activated low-calcium fly ash solidified soils dredged
- 557 from East Lake, China, Mar. Georesour. Geotec. (2019) DOI:
 558 10.1080/1064119X.2019.1648616.
- 559 [4] D. Wang, N. E. Abriak, R. Zentar, One-dimensional consolidation of lime-treated

25

- ⁵⁶⁰ dredged harbour sediments, Eur. J. Environ. Civil En. 19(2) (2015) 199-218.
- 561 [5] D. Wang, L. Korkiala-Tanttu, On the normalized behaviour of naturally and 562 artificially structured clays, Eng. Geol. 214 (2016) 20-28.
- 563 [6] D. Wang, N. E. Abriak, R. Zentar, Temperature-accelerated strength development
- in stabilised marine soils as road construction materials, J. Mater. Civil Eng. 2017,
 29(5): 04016281.
- 566 [7] B. K. Dahal, J. J. Zheng, R. J. Zhang, D. B. Song, Enhancing the mechanical
- properties of marine clay using cement solidification, Mar. Georesour. Geotec. 37(6)(2019) 755-764.
- [8] L. Liu, A. Zhou, Y. Deng, Y. Cui, Z. Yu, C. Yu, Strength performance of
 cement/slag-based stabilized soft clays, Constr. Build. Mater. 211 (2019) 909-918.
- 571 [9] P. Jamsawang, H. Poorahong, N. Yoobanpot, S. Songpiriyakij, P. Jongpradist,
- Improvement of soft clay with cement and bagasse ash waste, Constr. Build. Mater.
 154 (2017) 61-71.
- 574 [10] X. Kang, G. C. Kang, K. Chang, L. Ge, Chemically stabilized soft clays for
 575 road-base construction, J. Mater. Civil Eng. 27(7) (2015) 04014199.
- 576 [11] Y. X. Wang, P. P. Guo, X. Li, H. Lin, Behavior of fiber-reinforced and
- 577 lime-stabilized clayey soil in triaxial tests, Appl. Sci.-Basel 9(5) (2019) 900.
- 578 [12] C. S. Tang, D. Y. Wang, Y. J. Cui, B. Shi, J. Li, Tensile strength of
 579 fiber-reinforced soil, J. Mater. Civil Eng. 28(7) (2016) 04016031.
- 580 [13] A. Ammar, S. Najjar, S. Sadek, Mechanics of the interface interaction between
- hemp fibers and compacted clay, Int. J. Geomech. 19(4) (2019) 04019015.

582	[14] Y. Wang, P. Guo, F. Dai, X. Li, Y. Zhao, Y. Liu, Behavior and modeling of
583	fiber-reinforced clay under triaxial compression by combining the superposition
584	method with the energy-based homogenization technique, Int. J. Geomech. 18(12)
585	(2018) 04018172.

- [15] Q. Ma, C. Gao, Effect of basalt fiber on the dynamic mechanical properties of
 cement-soil in SHPB test, J. Mater. Civil Eng. 30(8) (2018) 04018185.
- [16] M. E. Orakoglu, J. K. Liu, F. J. Niu, Dynamic behavior of fiber-reinforced soil
 under freeze-thaw cycles, Soil. Dyn. Earthq. Eng. 101 (2017) 269-284.
- [17] P. Sharma, An introduction to basalt rock fiber and comparative analysis ofengineering properties of BRF and other natural composites, International Journal for
- 592 Research in Applied Science & Engineering Technology 4(I) (2016) 141-147.
- 593 [18] H. Jamshaid, R. Mishra, A green material from rock: basalt fiber a review, J.
- 594 Text. I. 107(7) (2016) 923-937.
- 595 [19] C. Buratti, E. Moretti, E. Belloni, F. Agosti, Thermal and acoustic performance
- evaluation of new basalt fiber insulation panels for buildings, Energy Procedia 78(2015) 303-308.
- 598 [20] A. G. Novitskii, High-temperature heat-insulating materials based on fibers from
- basalt-type rock materials, Refract. Ind. Ceram. 45(2) (2004) 144-146.
- 600 [21] E. Moretti, E. Belloni, F. Agosti, Innovative mineral fiber insulation panels for
- buildings: Thermal and acoustic characterization, Appl. Energ. 169 (2016) 421-432.
- 602 [22] Y. V. Lipatov, S. I. Gutnikov, M. S. Manylov, E. S. Zhukovskaya, B. I. Lazoryak,
- High alkali-resistant basalt fiber for reinforcing concrete, Mater. Design 73 (2015)

604 60-66.

- 605 [23] A. B. Kizilkanat, N. Kabay, V. Akyüncü, S. Chowdhury, A. H. Akça, Mechanical
- 606 properties and fracture behavior of basalt and glass fiber reinforced concrete: An
- experimental study, Constr. Build. Mater. 100 (2015) 218-224.
- 608 [24] JTG E40-2007, Test Method of Soils for Highway Engineering, Ministry of
- Transport of PRC., Beijing: China Communications Press, 2007.
- 610 [25] C. Tang, B. Shi, W. Gao, F. Chen, Y. Cai, Strength and mechanical behavior of
- 611 short polypropylene fiber reinforced and cement stabilized clayey soil, Geotext.
- 612 Geomembranes 25(3) (2007) 194-202.
- 613 [26] D. Wang, N. E. Abriak, R. Zentar, W. Y. Xu, Solidification/stabilization of
- dredged marine sediments for road construction, Environ. Technol. 33(1) (2012)95-101.
- 616 [27] J. Prabakar, R. S. Sridhar, Effect of random inclusion of sisal fibre on strength
- 617 behaviour of soil, Constr. Build. Mater. 16(2) (2002) 123-131.
- 618 [28] C. S. Tang, B. Shi, L. Z. Zhao, Interfacial shear strength of fiber reinforced soil,
- 619 Geotext. Geomembranes 28(1) (2010) 54-62.
- 620 [29] N. Cristelo, V. M. Cunha, M. Dias, A. T. Gomes, T. Miranda, N. Araújo,
- 621 Influence of discrete fibre reinforcement on the uniaxial compression response and
- seismic wave velocity of a cement-stabilised sandy-clay, Geotext. Geomembranes
 43(1) (2015) 1-13.
- [30] H. Li, X. Guan, X. Zhang, P. Ge, X. Hu, D. Zou, Influence of superfine ettringite
- on the properties of sulphoaluminate cement-based grouting materials, Constr. Build.

- 626 Mater. 166 (2018) 723-731.
- 627 [31] O. A. Alawad, A. Alhozaimy, M. S. Jaafar, A. Al-Negheimish, F. N. A. Aziz,
- 628 Microstructure analyses of autoclaved ground dune sand-Portland cement paste,
- 629 Constr. Build. Mater. 65 (2014) 14-19.
- [32] M. R. Ahmad, B. Chen, Effect of silica fume and basalt fiber on the mechanical
- 631 properties and microstructure of magnesium phosphate cement (MPC) mortar, Constr.
- 632 Build. Mater. 190 (2018) 466-478.
- 633 [33] D. Wang, L. Korkiala-Tanttu, 1-D compressibility behaviour of cement-lime
- 634 stabilized soft clays, Eur. J. Environ. Civ. En. (2019) DOI
 635 10.1080/14680629.2018.1439400.
- [34] D. Wang, X. Gao, R. Wang, S. Larsson, M. Benzerzour, Elevated curing
 temperature-associated strength and mechanisms of reactive MgO-activated industrial
 by-products solidified soils, Mar. Georesour. Geotec. (2019) DOI:
 10.1080/1064119X.2019.1610817.
- 640 [35] D. Wang, J. Zhu, F. He, Quantification and micro-mechanisms of CO₂
 641 sequestration in magnesia-lime-fly ash/slag solidified soils, Int. J. Greenh. Gas Con.

642 91 (2019) 102827.

- [36] D. Wang, J. Zhu, F. He, CO₂ carbonation-induced improvement in strength and
 microstructure of reactive MgO-CaO-fly ash-solidified soils, Constr. Build. Mater.
 229 (2019) 116914.
- 646 [37] D. Wang, J. Xiao, F. He, Y. Zhou, Durability evolution and associated
 647 micro-mechanisms of carbonated reactive MgO-fly ash solidified sludge from East

- 648 Lake, China, Constr. Build. Mater. 208 (2019) 1-12.
- 649 [38] D. Wang, J. Xiao, X. Gao, Strength gain and microstructure of carbonated
- reactive MgO-fly ash so-lidified sludge from East Lake, China, Eng. Geol. 251 (2019)
- 651 37-47.

Figures

Fig. 1 Basalt fibers used in this study

(a) Dispersed 3-mm length fiber	(b) Dispersed 7-mm length fiber
(c) Dispersed 11-mm length fiber	(d) Clustered 3-mm length fiber
(e) Clustered 7-mm length fiber	(f) Clustered 11-mm length fiber

Fig. 2 Stress-strain analysis of kaolinite samples under varying basalt fiber contents at 28 d

(a) BFUK (b) BFCK

Fig. 3 Compressive strength of kaolinite samples under varying basalt fiber contents

(a) BFUK (b) BFCK

Fig. 4 Typical deviatoric stress-strain relationships by triaxial tests on BFCK samples

(a) At varying basalt fiber contents and confining pressure of 100 kPa

(b) At varying basalt fiber lengths and confining pressure of 100 kPa

(c) At varying confining pressures for samples K6P0.2B-11 and K6P0B

Fig. 5 Variation of deviatoric stress at peak state and peak stress ratio with varying basalt fiber contents

(a) peak deviatoric stress (b) peak stress ratio

Fig. 6 Variation of peak deviatoric stress and peak stress ratio with varying basalt fiber lengths at 0.2 % basalt fiber

(a) peak deviatoric stress (b) peak stress ratio

Fig. 7 Variation of peak deviatoric stress and peak stress ratio at varying confining

pressures

(a) peak deviatoric stress (b) peak stress ratio

Fig. 8 SEM images and EDX patterns of typical specimens

- (a) BFUK with 0.2 % basalt fiber ($\times 2000$)
- (b) local marked magnified area of (a) (×5000)
- (c) BFCK with 0.2 % basalt fiber (×2000)
- (d) local marked magnified area of (c) (×5000)
- (e) EDX pattern of AFt
- (f) EDX pattern of C-S-H

Fig. 9 Distribution of basalt fibers in BFCK

- (a) 0.1 % basalt fiber (×200) (b) 0.2 % basalt fiber (×200)
- (c) 0.3 % basalt fiber (×200)

Fig. 10 Experimental evidence of friction between fiber and kaolinite

- (a) pullout of basalt fibers forms a scratch on the kaolinite section
- (b) a scratch at the end of basalt fiber
- (c) lots of scratches on the polypropylene fiber surface (from Tang et al. [29])

Fig. 11 Sketch of interfacial mechanical behavior between kaolinite particles, cement

hydration products and basalt fibers



Fig. 1 Basalt fibers used in this study



(b) BFCK

Fig. 2 Stress-strain analysis of kaolinite samples under varying basalt fiber contents at





Fig. 3 Compressive strength of kaolinite samples under varying basalt fiber contents



(a) At varying basalt fiber contents and confining pressure of 100 kPa



(b) At varying basalt fiber lengths and confining pressure of 100 kPa



(c) At varying confining pressures for samples K6P0.2B-11 and K6P0BFig. 4 Typical deviatoric stress-strain relationships by triaxial tests on BFCK samples



(a) Peak deviatoric stress





Fig. 5 Variation of deviatoric stress at peak state and peak stress ratio with varying

basalt fiber contents



(b) Peak stress ratio

Fig. 6 Variation of peak deviatoric stress and peak stress ratio with varying basalt fiber lengths at 0.2 % basalt fiber





Fig. 7 Variation of peak deviatoric stress and peak stress ratio at varying confining

pressures



(a) BFUK with 0.2 % basalt fiber ($\times 2000$)

(b) local marked magnified area of (a)

(×5000)



(c) BFCK with 0.2 % basalt fiber (×2000)

(d) local marked magnified area of (c)

(×5000)





Fig. 8 SEM images and EDX patterns of typical specimens



(a) 0.1 % basalt fiber (×200)

(b) 0.2 % basalt fiber (×200)

(c) 0.3 % basalt fiber (×200)

Fig. 9 Distribution of basalt fibers in BFCK

(a) pullout of basalt fibers forms a scratch on the kaolinite section (b) a scratch at the

end of basalt fiber

(c) lots of scratches on the polypropylene fiber surface (from Tang et al. [25])

Fig. 10 Experimental evidence of friction between fiber and kaolinite

Fig. 11 Sketch of interfacial mechanical behavior between kaolinite particles, cement

hydration products and basalt fibers

Tables

Table 1 Basic physical characteristics of kaolinite

Table 2 Chemical compositions of ordinary Portland cement

Table 3 Technical specifications of employed basalt fiber

Table 4 Mix formulations (wt%) for UCS and CU triaxial tests

Table 1 Basic physical characteristics of kaolinite

Parameters	Values
Initial water content (%)	0.17
Specific gravity	2.75
Liquid limit (%)	31.0
Plastic limit (%)	20.1
Plasticity index (%)	10.9
Optimum water content (%)	22.4
Maximum dry density (g/cm ³)	1.62

Table 2 Chemical compositions of ordinary Portland cement

Chemical composition	Content by mass (%)			
CaO	62.4			
SiO ₂	22.6			
Al ₂ O ₃	5.7			
Fe ₂ O ₃	4.3			
MgO	0.8			
SO ₃	1.1			
Other oxides	3.1			

Parameter	Value		
Fiber type	Monofilament		
Density (g/cm ³)	2.63		
Diameter (µm)	7-15		
Tensile strength (MPa)	3000-4800		
Modulus of elasticity (GPa)	91-110		
Melting point (°C)	1050		
Acid and alkali resistance	Excellent		

Table 3 Technical specifications of employed basalt fiber

Types of			Content (% by weight)			Length of	Curing
tests	Group	Mixture ID	Kaolinite	Cement	Basalt fiber	basalt fiber (mm)	time (d)
		K0B	100	0	0		3, 7, 14, 28
		K0.1B	99.9	0	0.1	11	3, 7, 14, 28
	1	K0.2B	99.8	0	0.2	11	3, 7, 14, 28
		K0.3B	99.7	0	0.3	11	3, 7, 14, 28
LICS test		K0.4B	99.6	0	0.4	11	3, 7, 14, 28
UCS lest		K6P0B	94	6	0		3, 7, 14, 28
	2	K6P0.1B	93.9	6	0.1	11	3, 7, 14, 28
		K6P0.2B	93.8	6	0.2	11	3, 7, 14, 28
		K6P0.3B	93.7	6	0.3	11	3, 7, 14, 28
		K6P0.4B	93.6	6	0.4	11	3, 7, 14, 28
		K6P0B	94	6	0		7
		K6P0.1B	93.9	6	0.1	11	7
	2	K6P0.2B	93.8	6	0.2	11	7
	3	K6P0.3B	93.7	6	0.3	11	7
CU TC test		K6P0.4B	93.6	6	0.4	11	7
		K6P0.5B	93.5	6	0.5	11	7
		K6P0.2B-3	93.8	6	0.2	3	7
	4	K6P0.2B-7	93.8	6	0.2	7	7
		K6P0.2B-11	93.8	6	0.2	11	7