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INFLUENCE OF CEMENT CONTENT AND MOISTURE CONTENT ON THE PULLOUT-INTERFACE PROPERTIES OF GEOGRID-SOLIDIFIED WASTE MUD

VPLIV VSEBNOSTI CEMENTA IN VLAGE NA MEHANSKE LASTNOSTI NARAVNO STRJENEGA ODPADNEGA BLATA

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In engineering, waste mud is often used as a filling material after a solidification treatment. Geogrids, being excellent geotechnical engineering materials, are often used for soil reinforcement. In this work, a pullout test that considered the influence of different waste-mud moisture contents and cement contents was conducted to investigate the interface characteristics of geogrid-solidified waste-mud-reinforced soil. Then, the relationship between the pullout force and displacement, and the variations in the cohesion, friction angle and quasifriction coefficient were analysed. The results showed that the pullout force-displacement curve represented a strain-softening pattern. With the increasing moisture content, the peak pullout force, interfacial cohesion and quasifriction coefficient decreased gradually, but the internal friction angle did not change substantially. With the increasing cement content, the peak pullout force, interfacial cohesion, internal friction angle and quasifriction coefficient increased gradually. The peak pullout force was linearly correlated with the change in the moisture content and logarithmically correlated with the change in the cement content. Compared with the moisture content, the reinforcement-soil interface was more affected by the cement content. This study provides guidelines for the mixture design of reinforced solidified waste mud.

Keywords: geogrid, solidification, cement content, interface characteristics, pullout test

V gradbeništvu se odpadno blato pogosto uporablja kot polnilni material po obdelavi s strjevanjem. Geološke mreže oziroma krajše geomreže so odličen geotehniški gradbeni material in se pogosto uporabljajo za utrjevanje zemljine oziroma terena. V tem članku avtorji opisujejo izvedbo nateznega preizkusa (angl.: pullout test) z doma izdelano napravo, da bi ocenili obnašanje različnih vrst strjenega odpadnega blata na geomreži. Ugotavljali so vpliv vsebnosti cementa in vlage v blatu na mejne lastnosti in ojačitev med strjenim blatom in geomrežo. Nato so poiskali zvezo med vlečno silo in pomikom ter različne kohezijske zakone, analizirali kot trenja in kvazi koeficient trenja. Rezultati preizkusov so pokazali, da se krivulje sila vleka-pomik obnašajo v načinu deformacijskega mehčanja. Z naraščajočo vsebnostjo vlage se postopoma zmanjšujejo vršnja (maksimalna) sila vleka, medmejna kohezija in koeficient trenja, toda notranji kot trenja se ni bistveno spremenil. Z naraščajočo vsebnostjo cementa pa so se postopoma poviševali vršnja sila vleka, notranji kot trenja in kvazi koeficient trenja. Vršnja sila je bila linearno odvisna od vsebnosti vlage v blatu, medtem ko je bila le-ta logaritmično odvisna od spremembe vsebnosti cementa. Na mejno kohezijo med geomrežo in blatom je najbolj vplivalo povečevanje vsebnosti cementa. Avtorji poudarjajo, da izvedena študija lahko služi kot vodilo za oblikovanje ojačitve strjenega odpadnega blata.

Ključne besede: geomreža, strjevanje, vsebnost cementa, lastnosti na mejnih ploskvah, vlečni preizkus

1 INTRODUCTION

With the advancement of urbanisation construction, underground-space development and transportation-infrastructure construction in China, a large amount of engineering waste mud has been produced during the construction of bored piles, shield tunnelling and underground diaphragm walls; a large amount of dredged mud is also produced within annual channel dredging projects. Given the extremely high moisture content of engineering waste mud and dredged mud, which belong to the category of fluid mud with almost zero strength, they cannot be directly used for engineering construction and can be classified as waste. Its improper treatment can easily cause disorderly discharge, environmental pollution and ecological damage.[1,2] Consequently, solidification treatment of waste mud has become a common method of the resource utilisation. Solidified waste mud can be directly filled into foundations or temporarily placed in storage after treatment, after which it can be widely used in road, embankment, foundation and slope filling.[3]

Geosynthetics are new types of geotechnical engineering material including synthetic polymers (e.g., plastic, chemical fibre and synthetic rubber) utilised as raw materials. Adding geosynthetics, such as geogrids and geocells, to fillings not only enhances the stability of soil but also improves the overall soil strength.[4,5] At present, geosynthetic materials have been widely used in slope reinforcement and foundation treatment. The characteristics of reinforced soil are important for the structural design and stability analysis of geosynthetic-reinforced soil. Scholars at home and abroad have attempted to characterise the interface between different types of soil

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and geogrids.[6–8] Razzazan et al.[9] investigated the effects of various factors, such as load amplitude and frequency, number of load cycles and vertical effective stress, on the pullout resistance and peak apparent coefficient of friction mobilised at buried polymeric strip-soil interfaces. Wang Xiongjin[10] obtained the stress-strain curve of a geotextile-cement soil interface by conducting a large-scale direct shear test and then analysed the influence of the cement content on the interface strength. Jinqing et al.[11] conducted an interface pullout test on sensing geosynthetics and weathered rock material-tire shred lightweight soil and established a hyperbolic constitutive model based on the reinforced-soil interaction. Abdi and Arjomand[12] conducted pullout tests on clay reinforced with geogrids encapsulated in thin layers of sand and found that geogrids encapsulated in such thin layers can improve the tensile properties of reinforced clay. Liu Feiyu et al.[13] conducted a series of cyclic shear tests on sandwich-reinforced soil using a large direct shear apparatus and studied the effects of different thin sand layer thicknesses, cyclic shear amplitudes and vertical stresses on interface shear characteristics. Chen Rong et al.[14] conducted a series of geogrid-frozen soil pullout tests on silty clay in Northeast China and analysed the effects of the soil moisture content and freeze-thaw cycle on the reinforcement performance of the geogrid. Their results showed the apparent inhibitory effect of the moisture content on the geogrid reinforcement, with the freeze-thaw cycle improving the reinforcement effect of this geogrid. Yi Fu et al.[15] comparatively studied the interface characteristics of geogrids with different mesh sizes and tailings and established the control measure for the geogrid mesh size when the area ratio of the geogrid-tailings interface to the shear surface is approximately 0.4.

A combined application of geotechnical reinforcement and cement-solidified waste-mud technology in foundation and slope engineering can greatly improve the strength and stability of soil. However, research on the characteristics of the interface between geogrids and solidified waste mud is limited. In this study, indoor pullout tests were performed to investigate the pullout force-displacement relationship of geogrid-solidified waste-reinforced soil. The influences of different moisture contents of waste mud and different cement contents were determined to analyse the changes in the cohesion, friction angle and interfacial quasifriction coefficient and provide a reference for the application of reinforced solidified waste mud.

2 TEST SCHEME

2.1 Test equipment

An in-house-made pullout instrument was used to perform the pullout test on the interface of the reinforced soil. The test equipment is shown in **Figure 1** and the geogrid is shown in **Figure 2**. The internal dimensions of the pullout test box are (12.5 × 12.5 × 25) cm (length × width × height). Acrylic plates were set on all sides of the test box to observe the deformation of the solidified waste mud and the displacement of the geogrid during the test. The horizontal loading system was composed of a pullout displacement device, tension controller and fixture. During the test, the controller was set to a constant pullout rate or constant pullout force, with a maximum pulling force as high as 10 kN. The vertical loading system was composed of an air compressor, cylinder, pressure controller and gasket. Normal pressure was applied to the specimen by adjusting the pressure value of the controller.

2.2 Test materials

Muck soil from Funing, Jiangsu, China, was selected as the waste mud. This soil type is characterised by a high moisture content, low strength, high organic matter content, high compressibility, low shear strength and poor water permeability; thus, it cannot be directly used

Figure 1: In-house-made pullout test equipment

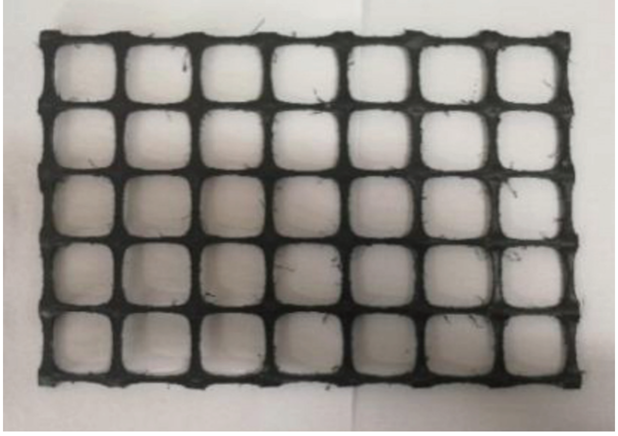

Figure 2: Geogrid

Table 1: Technical data of the geogrid

Product specification	Transverse rib width (mm)	Longitudinal rib width (mm)	Transverse rib thickness (mm)	Longitudinal rib thickness (mm)	Mesh size (mm)	Longitudinal / transverse ultimate tensile strength per linear meter ($kN \cdot m^{-1}$)	Pullout force at longitudinal / transverse elongation of 2 % ($kN \cdot m^{-1}$)	Pullout force at longitudinal / transverse elongation of 5 % ($kN \cdot m^{-1}$)
TGSG5050	3.5	2.5	2.0	3.5	30 × 30	≥50	≥17	≥34

Table 2: Test cases

Sequence number	Moisture content (w_L)	Cement content (kg/m^3)	Age (d)	Normal pressure P (kPa)
1	1.5	100	28	50, 100, 150
2	2.0	100		
3	2.5	100		
4	2.0	50		
5	2.0	150		

and must be cured. In this study, Funing PO42.5 Portland cement was used as the curing agent. A hybrid liquid-plastic limit tester was used to determine the moisture content limit for the mud in the Funing area. The liquid limit w_L for the mud in Funing was 52 %. The sample was prepared via stratification. When the solidified mud reached the middle height of the pullout box, a tensile plastic bidirectional geogrid was laid down. After laying, solidified mud was continuously injected to the top of the pullout box. The curing was completed in 28 d. The pullout test was conducted by applying three normal pressures of (50, 100 and 150) kPa. Bidirectional plastic geogrid developed by Hebei Zhonghui Rubber and Plastic Products Co., Ltd., was used for this study. The size of the geogrid applied in the test was (110 × 75) mm (length × width). Specific indicators are shown in **Table 1**.

2.3 Pullout tests

The moisture content of the waste mud and cement content were taken as test variables. The single control variable method was adopted in the pullout test of the reinforced solidified waste mud, with the water and cement contents varying at a pullout rate of 1 mm/min. Specific test details are shown in **Table 2**.

3 RESULT AND ANALYSIS

3.1 Relationship between the pullout force and displacement

Figures 3 and **4** show the relationship curves between the typical pullout force and displacement under different conditions. The varying shapes of the pullout force-displacement curves are essentially the same. With the increasing pullout displacement, the curves first increased rapidly, and the growth rate gradually decreased after reaching the peak, generally depicting a strain-softening pattern. With the increasing normal pressure, the pullout force at the same loading displacement was large. The pullout displacement of the geogrid was also large when it reached the peak value. The relationship between the pullout force and displacement can be divided into three stages: rapid growth, slow growth and failure. In the rapid growth stage, as the main action between the geogrid and solidified waste mud was friction, the pullout force increased rapidly with the pullout displacement. In the slow growth stage, given the interlocking and occluding effect of the geogrid mesh, the pulling force slowed down with the decreasing displacement growth rate and slowly reached the peak value. The outer surface with the embedded geogrid in the middle of the sample cracked and the bond in the solidified mud decreased. In the failure stage, after the pullout force reached the peak, the interface between the geogrid and solidified waste mud changed into a complete crack. The residual bond strength and normal pressure of the solidified mud were insufficient to bind the geogrid and mud, and the pullout force slowly decreased. The trends indicate that the pullout resistance of the geogrid-solidified mud interface comprises two parts in the pullout process. The first part was the friction resistance between the geogrid and the solidified mud. The second part was the interlocking effect of the geogrid mesh in the solidified mud, especially the passive resistance of the transverse rib, in which the loss of the bonding strength of the solidified mud significantly affected the interface characteristics. The lower the moisture content and the higher the cement content, the greater is the pullout force under the same pullout displacement.

3.2 Variation in the peak value of the pullout force

Figure 5 shows variation curves of the peak pulling forces of the geogrid-solidified mud under different normal pressures. The peak value of the pullout force increased with the increasing normal pressure under different normal pressures, and the variation curve presented an approximately linear distribution. The growth trends of [2.5 w_L, 100 kg/m^3], [2.0 w_L, 100 kg/m^3], [1.5 w_L, 100 kg/m^3] and [2.0 w_L, 150 kg/m^3] were essentially the same. For example, under the condition of the 2.0 w_L

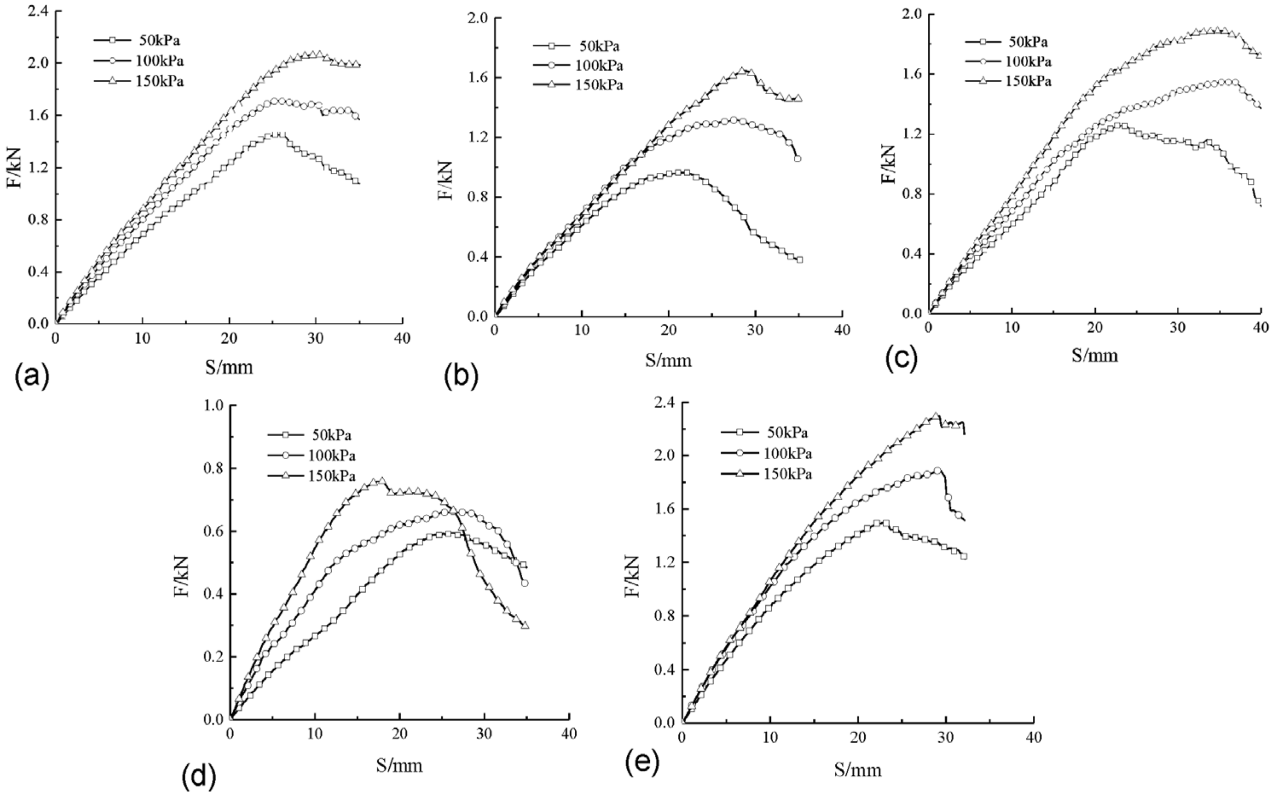

Figure 3: Relationship curves between typical pullout force and displacement under different normal pressures: a) 1.5 w_L, 100 kg/m^3, b) 2.5 w_L, 100 kg/m^3, c) 2.0 w_L, 100 kg/m^3, d) 2.0 w_L, 50 kg/m^3, e) 2.0 w_L, 150 kg/m^3

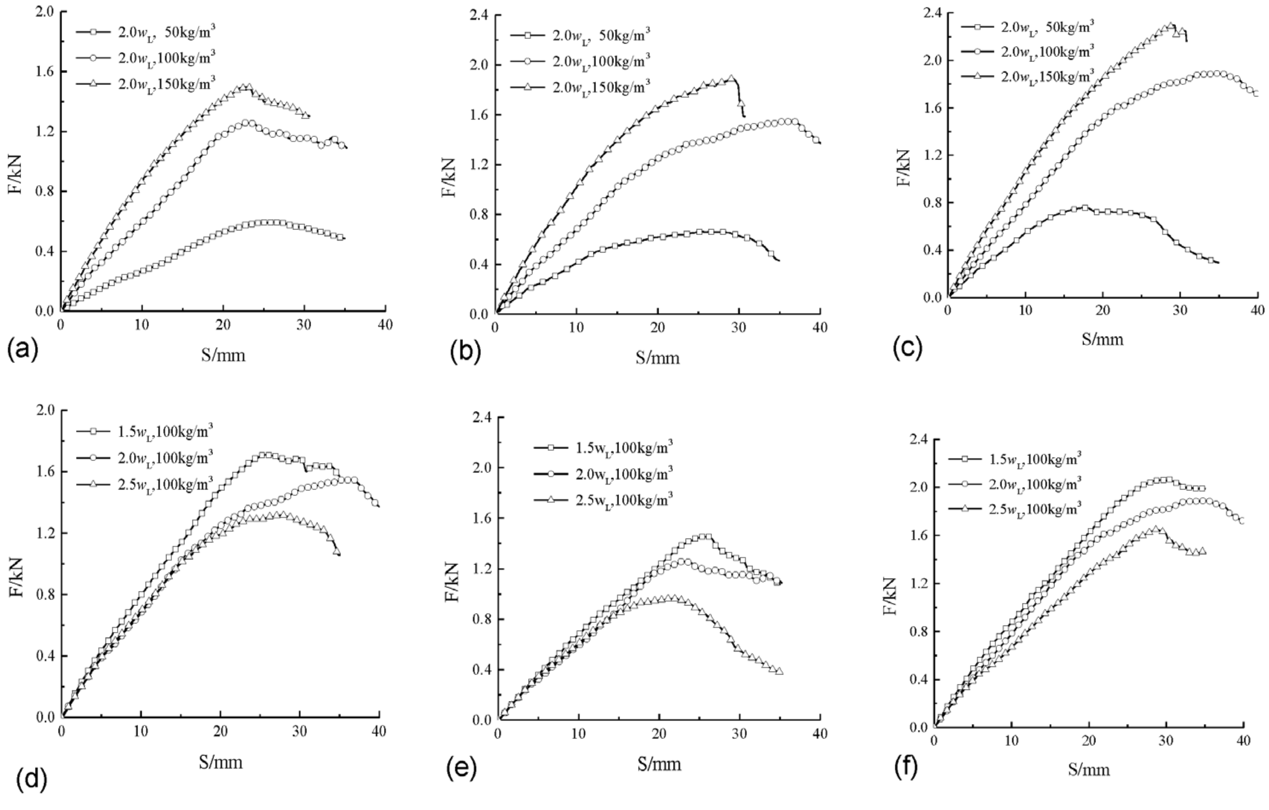

Figure 4: Relationship curves between typical pullout force and displacement under different moisture and cement contents: a) P = 50 kPa, w = 2.0 w_L, b) P = 100 kPa, w = 2.0 w_L, c) P = 150 kPa, w = 2.0 w_L, d) P = 100 kPa, C = 100kg/m^3, e) P = 50 kPa, C = 100 kg/m^3, f) P = 150 kPa, C = 100 kg/m^3

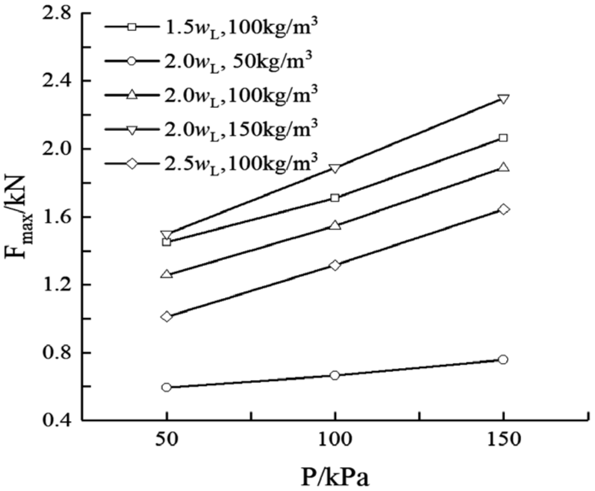

Figure 5: Variation curves of peak pullout forces under different normal pressures

moisture content and 150 kg/m^3 cement content, the peak values of the pullout force under (50, 100 and 150) kPa normal pressures were (1.499, 1.889 and 2.298) kN, respectively, showing an increase by 26.0 % and 21.7 % with respect to their original values. However, under the conditions of [2.0 w_L, 50 kg/m^3], the growth curves of the peak pullout force changed, shifting to 0.594, 0.663 and 0757 kN, respectively, showing an increase by only 11.6 % and 14.2 % with respect to their original values. These values were much lower than those under the previous working conditions.

3.3 Influence of the moisture content and cement content on the pullout force

The variation curves for the peak value of the pullout force with the moisture content and cement content were fitted. In this manner, the influence of different moisture contents and cement contents on the peak value of the pullout force could be analysed. The correlation coefficients were higher than 0.987, showing a good degree of fitting (**Figures 6** and **7**). **Figure 6** shows that under the same normal pressure, the peak value of the pullout force at different moisture contents decreases with an increasing moisture content, while the reduction rate is essentially the same. The relationship between the peak value of the pullout force and moisture content follows the linear function formula. **Figure 7** shows that under the same normal pressure, the peak value of the pullout force at different cement contents gradually increases with an increasing cement content. The larger the cement content, the smaller is the growth rate. The relationship between the peak value of the pullout force and the cement content follows the logarithmic function formula. The greater the normal stress, the greater is the growth rate of the peak value of the pullout force.

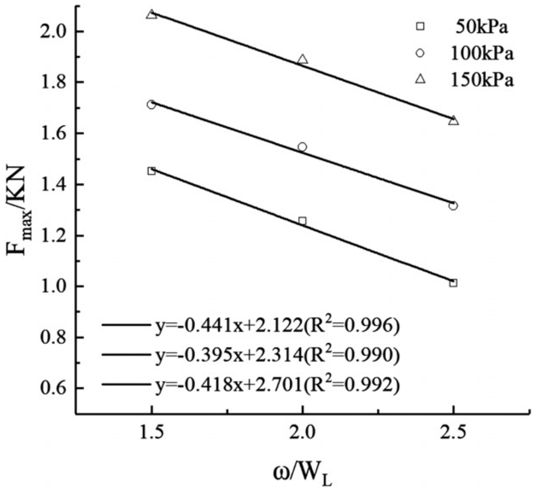

Figure 6: Variation curves of peak pullout force with moisture content

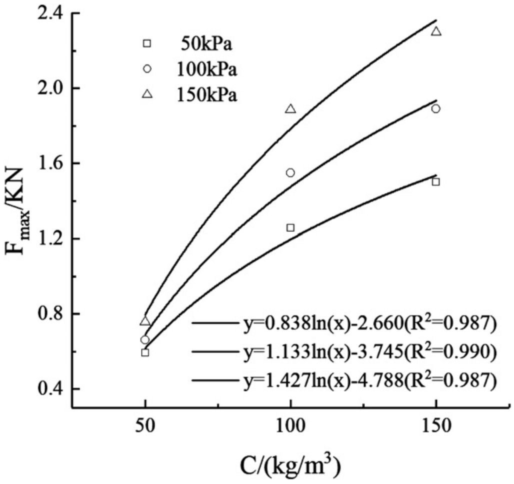

Figure 7: Variation curves of peak pullout force with cement content

3.4 Variation in the interfacial cohesion and internal friction angle

Figures 8a and **8b** show the relationship between interfacial shear stress and normal pressure under different moisture contents and cement contents, respectively. The variation trends for the shear stress under different moisture contents and cement contents are essentially the same (i.e., they increase with the increasing normal stress). Then, the curves were linearly fitted to analyse the variation in the cohesion and internal friction angle under different moisture contents and cement contents. The correlation coefficients of the fitted lines were all higher than 0.992, indicating a good fitting degree. The slope difference of each fitting curve under different cement contents was greater than that under different moisture contents. This finding reflects a considerable influence of the cement content on the interfacial shear stress.

The results of the linear fitting formula were further analysed to obtain the interfacial cohesion and internal friction under various conditions (**Table 3**). As the moisture content increased, the cohesion decreased gradually, whilst the internal friction angle increased slightly. Meanwhile, as the cement content increased, the cohe-

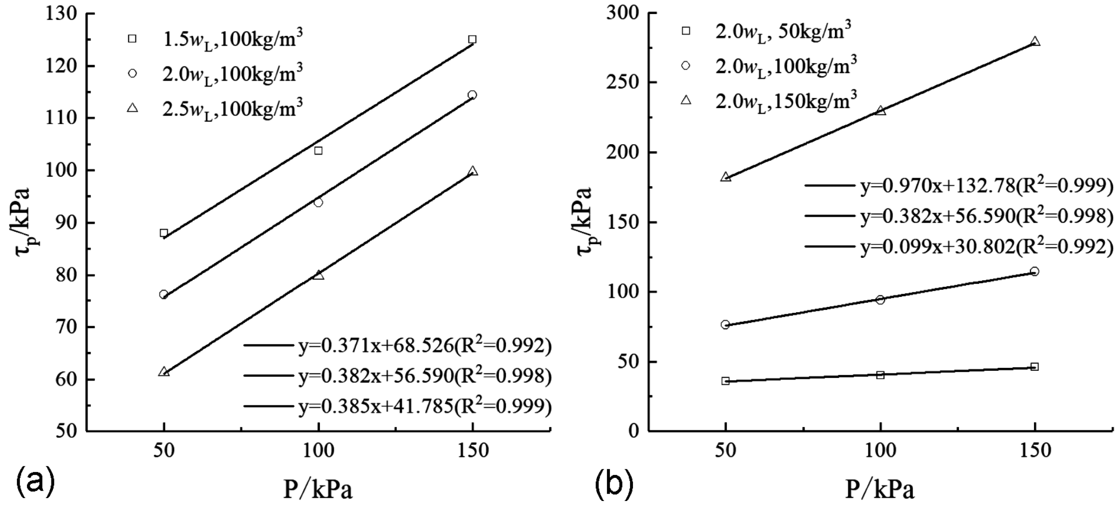

Figure 8: Variation in interfacial shear stress with normal stress: a) different moisture contents, b) different cement contents

sion and internal friction angle increased gradually. With regard to the moisture content, the difference in the cohesion and internal friction angle between varying cement contents is large, indicating a greater influence of the cement content than that of the moisture content on the interfacial strength index.

Table 3: Interfacial cohesion and internal friction angle under different conditions

Moisture content (w_L)	Cement content (kg/m^3)	C (kPa)	φ (°)
1.5	100	68.526	20.334
2.0	100	56.590	20.912
2.5	100	41.785	21.052
2.0	50	30.802	5.651
2.0	150	132.78	44.138

3.5 Variation in the interfacial quasifriction coefficient

The quasifriction coefficient of the reinforced soil interface was calculated and then analysed to intuitively characterise the reinforced soil interface. The calculation formula for the quasifriction coefficient *f* is

$$f = \frac{F_{\max}}{2\sigma_n^{'} LB} \tag{1}$$

where $F_{\max}$ is the peak value of the pullout force measured in the test, L and B are the effective pullout length and width of the geogrid, respectively, and $\sigma_n{}'$ is the total normal pressure on the geogrid interface, i.e., the sum of the normal stress applied in the test and the dead weight stress of the soil above the grid. **Figure 9** shows the variation curves for the quasifriction coefficient at the surface under different moisture and cement contents. Under different normal pressures of (50, 100 and 150) kPa, the quasifriction coefficients under the 1.5 w_L moisture content and 100 kg/m^3 cement content were 1.760, 1.037 and 0.834, respectively, decreasing by 41.1 % and 19.6 % with respect to their original values. In particular, the quasifriction coefficients under the 2.0 w_L moisture content and 50 kg/m^3 cement content were 0.716, 0.402 and 0.306, decreasing by 43.9 % and 23.9 % with respect to their original values. The quasifriction coefficients under the 2.0 w_L moisture content and 100 kg/m^3 cement content were 1.524, 0.938 and 0.762, decreasing by 38.5 % and 18.8 % with respect to their original values. The quasifriction coefficients under the 2.0 w_L moisture content and 150 kg/m^3 cement content were 1.816, 1.145 and 0.929. Finally, the quasifriction coefficients under the 2.5 w_L moisture content and 100 kg/m^3 cement content were 1.225, 0.797 and 0.665, decreasing by 34.9 % and 16.6 % with respect to their original values. As the moisture content increased or the cement content decreased, both the quasifriction coefficient and reduction rate decreased gradually with the increasing normal pressure. The variation ranges of the quasifriction coefficient attributed to the change in the cement content were larger than those attributed to the change in the moisture content.

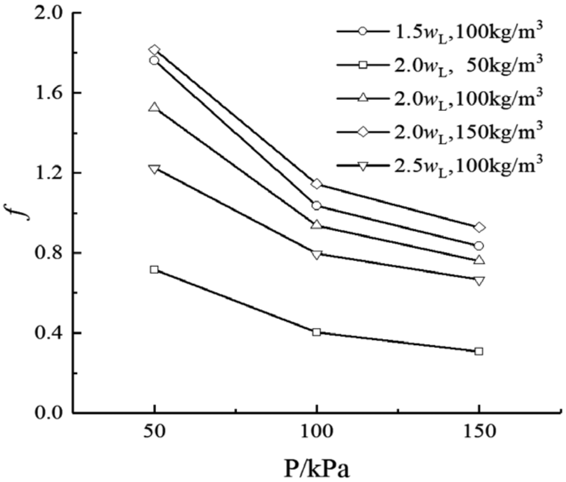

Figure 9: Variation curves of the interface quasifriction coefficient

4 CONCLUSIONS

A pullout test of geogrid-reinforced solidified waste mud, considering the influence of different moisture contents of waste mud and cement contents was conducted in this study. The relationship between the pullout force and displacement of reinforced soil was investigated, and the variations in the interfacial cohesion, friction angle and quasifriction coefficient were analysed. The main conclusions are as follows:

(1) The pullout force-pullout displacement curves of solidified waste mud with different moisture contents and cement contents under different normal pressures first increased rapidly with the increasing pullout displacement, then the growth rate decreased gradually and finally it decreased slowly after reaching the peak. This trend depicts strain-softening characteristics.

(2) The peak value of the pullout force decreased gradually with the increasing moisture content, and they were linearly related. The curve increased gradually with the increasing cement content, showing a logarithmic correlation. Compared with the moisture content, the cement content had a greater effect on the peak value of the pullout force.

(3) The interfacial shear stress, cohesion and quasifriction coefficient decreased gradually with the increasing moisture content, but the internal friction angle only changed slightly. With the increasing cement content, the interfacial shear stress, cohesion, internal friction angle and quasifriction coefficient increased gradually. The influence of the cement content on the interfacial strength was greater than that of the moisture content. Overall, this study can provide guidelines for the mixture design of solidified waste mud.

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