The short-term and creep mechanical behaviour of clayey soil-Geocomposite Drainage Layer interfaces subjected to environmental loadings

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Abstract: In this paper, to investigate the impact of environmental loadings on the short-term and creep mechanical characteristics of different types of clayey soil-Geocomposite Drainage Layers (GDL) interfaces, a series of rapid loading and creep shear tests were conducted on Mercia Mudstone Clay-GDL interfaces and Kaolin Clay-GDL interfaces subjected to drying-wetting cycles, thermal cycles and elevated temperature, etc, using a bespoke temperature and stress-controlled large direct shear apparatus. The experimental results indicate that, compared with the original specimens, the interfaces subjected to drying-wetting cycles, thermal cycles and elevated temperature, have lower peak shear strength and creep shear resistance. For example, under 25 kPa normal stress, the peak shear strength of original Mercia Mudstone Clay-GDL interfaces and Kaolin Clay-GDL interfaces falls by 11.91 % and 10.11 %, respectively, when subjected to 1 drying-wetting cycle. This can be ascribed to the weakening of interlocking effects and skin friction between soil and GDL caused by the softening of drainage core and geotextile fibres of GDL. The peak shear strength of clayey soil-GDL interfaces subjected to one drying-wetting cycle is lower than that subjected to one thermal cycle because of the reduction in the peak shear strength of clayey soil above GDL during drying-wetting cycles. The impact of drying alone on

the decrease in the peak shear strength of clayey soil-GDL interfaces during drying cycles with heating is small, and the main influence factor is the elevated temperature.

Keywords: Geosynthetics; Geocomposite Drainage Layers; interface shear strength; creep; drying-wetting cycles; thermal cycle

1 Introduction

Geocomposite Drainage Layers (GDL) are increasingly applied in a wide range of geotechnical and geoenvironmental applications, which can replace traditional solutions of adopting layers of graded sand and gravel to effectively drain excess water and reduce pore water pressure, improving the stability of engineering projects (Bahador et al., 2013; Chinkulkijniwat et al., 2017; Jang et al., 2015; Stormont et al., 2009). Especially for the GDL placed underneath cover soil above landfills, it can also provide separation and reinforcement functions and perform as a capillary break to prevent the migration of contaminated water and gas produced from waste materials (Khire and Haydar, 2007). For the engineering projects installed with GDL, their stability is mainly governed by the mechanical properties of interfaces between the GDL and adjacent soil (Othman et al., 2018). Thus, assessments of the mechanical characteristics for soil-GDL interfaces are vital for the application of GDL in engineering projects.

In the operational phase of engineering facilities installed with GDL, the soil-GDL interfaces within the facilities can experience both shear stresses and climatic loadings, such as, drying-wetting cycles, thermal cycles, and elevated temperature, etc (Bouazza et al., 2011; Fleureau et al., 2002; Koerner and Koerner, 2006). The environmental factors have non-negligible influences on the interaction mechanism between the installed GDL and adjacent soil, significantly changing the mechanical properties of the soil-GDL interfaces (Othman, 2016). For example, cover soil-GDL interfaces in landfills are usually exposed to elevated temperature due to exothermal reaction from waste biodegradation and hydration, with temperature ranging from 30 ℃ to 60 ℃ inside the landfills, decreasing the stiffness of the GDL (Abuel-Naga and Bouazza, 2013; Hanson et al., 2015; Jafari et al., 2014). Additionally, drying-wetting cycles and thermal cycles, generated by rainfall and ambient temperature variation, also have non-negligible impact on the mechanical properties of cover soil-GDL interfaces over the lifespan of landfills (Hosney and Rowe, 2013). This is because, in general, the thickness of cover soil for landfills is relatively small (about 0.5 m to 2 m), thus is susceptible to rain water and ambient air temperature cycles through its full thickness (McCartney and Zornberg, 2010). Whilst the high temperature inside landfills further accelerates the evaporation of water in the cover soil-GDL interfaces during drought, promoting the formation of obvious drying-wetting cycles on the cover soil-GDL interfaces during climatic changes, which may cause potential safety hazards on the long-term operation of landfills (Li et al., 2016).

In the existing investigations, the detrimental influences of elevated temperature and drying-wetting/thermal cycles on the mechanical properties of soil and polymer geosynthetics have been documented (Abuel-Naga and Bouazza, 2013; Guan et al., 2010; Ishimori and Katsumi, 2012; Singh and Bouazza, 2013). For instance, due to the presence of thermoplastic materials, the decrease in tensile strength and modulus of polymer geosynthetics occurs in elevated temperature (Wang et al., 2016; Zhang et al., 2015). Additionally, the decline in shear strength of soil was observed owing to the development of cracks and structure damage for the soil subjected to drying-wetting cycles (Guney et al., 2007; Md et al., 2016). However, due to the limitation of experimental equipment, studies about the mechanical responses of soil-geosynthetics interfaces subjected to environmental factors have rarely been reported, let alone the investigation of soil-GDL interfaces, because the conventional displacement-controlled direct shear apparatus cannot hold constant shear stresses whilst varying other parameters, such as, temperature, drying and wetting conditions, etc. to impose environmental loadings on the interfaces. Besides, it is impossible for the displacement-controlled direct shear apparatus to conduct creep tests on soil-geosynthetics interfaces (Fox and Stark, 2015). Moreover, the displacement-controlled direct shear tests that are not sufficiently representative of the real situation in engineering applications because, in reality, the shear displacement of soil-geosynthetics interfaces is controlled by stress rather than displacement (Frost and Karademir, 2016).

This is the second paper of two related papers. The first paper describes the bespoke stress and temperature-controlled large direct shear apparatus on soil-geosynthetics interfaces in detail (Chao and Fowmes, 2021). The aim of this second paper is to demonstrate in depth understanding of the mechanical responses of multiple of clayey soil-GDL interfaces under environmental loadings. A series of rapid loading direct shear tests and creep shear tests on Mercia Mudstone Clay-GDL interfaces and Kaolin Clay-GDL interfaces subjected to drying-wetting cycles, thermal cycles, and elevated temperature etc, were performed using the self-designed stress and temperature-controlled large direct shear apparatus, respectively. Whilst preliminary experimental results of Mercia Mudstone Clay-GDL interfaces have been presented in the first paper, this paper contains the full testing programme and allows the impacts of environmental factors on the short-term and creep mechanical characteristics of different kinds of clayey soil-GDL interfaces to be analysed.

2 Experimental program

2.1 Experimental apparatus

The bespoke temperature and stress-controlled large direct shear apparatus developed consists of four primary systems: normal stress system, shear stress system, heating system, and data acquisition and control system, as shown in Figure 1. The detailed introduction of the apparatus can be found in Chao and Fowmes (2021) .

2.2 Materials

2.2.1 Soil

Two types of soils were adopted in this paper:(1) Kaolin Clay and (2) Mercia Mudstone Clay. both derived from the UK. The Kaolin Clay and Mercia Mudstone Clay is classified as medium plasticity clay (CM) and low plasticity clay (CL) according to BS5930 (Dumbleton, 1981). The reason for selecting the two types of soil is to investigate and compare the impacts of environmental factors on mechanical properties of interfaces between GDL and clayey soils with different plasticity characteristics. The results of classification tests on the soil are presented in Table 1.

2.2.2 GDL

A proprietary GDL (6S250D/NW8) was adopted in this paper. The GDL is composed of a single cuspate HDPE (High Density Polyethylene) drainage core with a medium weight non-woven needle-punched and heat-treated staple fibre polypropylene geotextile filter thermally bonded on the dimple side and a lighter geotextile on the flat side. The GDL is often placed underneath the cover soil in landfills for drainage application, which is inevitably influenced by drying-wetting cycles, thermals cycles and elevated temperature. The properties of the GDL are shown in Table 2.

2.3 Preliminary sample preparation

Test samples were cut from a GDL roll, according to ASTM D 6072 (ASTM, 2008). The samples with 350 mm in width by 480 mm in length were cut so that shearing was carried out along the machine direction. GDL was clamped to the leading edge of the lower box. Then the upper shear box was filled with 13.02 kg or 13.50 kg of Mercia Mudstone Clay or Kaolin Clay at the optimum moisture content, 11.8 % or 20 %, in three equal increments, 25 mm height of each layer, respectively. The clay was then compacted adopting the light compaction method, and each layer was compacted with 16 blows of a tamper. The total height of the Mercia Mudstone Clay or Kaolin Clay specimen above the GDL was 75 mm with density 1.93 g/cm^3 or 2.00 g/cm^3, respectively. The gap between the upper and bottom shear boxes was adjusted to maintain approximately 1 mm during testing. During the tests, the dimple side of HDPE drainage core for the GDL was upward, and the pyramid-teeth penetrated into the geotextile bonded on the flat side of HDPE drainage core to prevent the relative movement between the GDL and the heating plate.

2.4 Experimental procedure

In the paper, both rapid loading shear tests and creep shear tests were carried out to research the short-term and creep mechanical behaviour of clayey soil-GDL interfaces subjected to environmental loadings, including drying-wetting cycles, thermal cycles and elevated temperature, etc, respectively, using the aforementioned self-designed stress and temperature-controlled large direct shear apparatus. Both the rapid loading shear tests and creep shear tests were conducted on two types of interfaces: Mercia Mudstone Clay-GDL interfaces and Kaolin Clay-GDL interfaces.

2.4.1 Rapid loading shear tests

Rapid loading shear tests show that, in the shearing process, shear load is continually increased until soil-GDL interfaces fail. The normal stress ranges from 15 kPa to 50 kPa to simulate 0.75-2.5 m of cover soil as is typical in the UK practice. The shearing was initiated after 24 hours consolidation, adding weights at a rate of 10 kg every 5 minutes, which was determined by trial and error. The detailed introduction of the tests is as follows:

(1) Standard rapid loading shear tests: The tests were carried out under normal stress of 15 kPa, 25 kPa and 50 kPa normal stress, at room temperature (22 °C).

(2) Tests under elevated temperatures: The process of the tests was almost the same with the standard tests, except that the whole process of the tests was conducted at an elevated temperature of 40 °C under normal stress of 15 kPa, 25 kPa and 50 kPa.

(3) Tests subjected to drying-wetting cycles: In the tests, after 24 hours consolidation, the drying process was initiated. Water in the external shear box was discharged, and the heating system was turned on to dry the interface at a constant temperature of 40 °C for 24 hours. After that, the wetting process was

started. The heating system was turned off, and water was poured into the external shear box to submerge the interface for 24 hours. This accounts for a single cycle. The cycle was repeated until the required number was reached. Then, the shearing process was conducted on the interface with it submerged into water. In this research, tests after 0,1 and 3 drying-wetting cycles were implemented under normal stresses of 15 kPa, 25 kPa and 50 kPa.

(4) Tests subjected to thermal cycle: The procedure of the tests was almost the same as the tests subjected to drying-wetting cycles, except that during the drying processes, the interfaces were submerged into water. In this case, tests after 1 thermal cycle were conducted under normal stress of 15 kPa, 25 kPa and 50 kPa, respectively.

(5) Tests subjected to drying-wetting cycle without heating: The procedure of the tests was almost the same as the tests subjected to drying-wetting cycles, except that during the drying process, only water in the external shear box was discharged and the heating system remained switched off to dry interfaces at room temperature of 22 °C for 7 days. In this case, tests after one drying-wetting cycle without heating was conducted under normal stress 25 kPa.

In order to research the moisture content variation of clay samples under drying-wetting cycle, thermal cycle and drying cycle without heating, the moisture contents of Mercia Mudstone Clay and Kaolin Clay specimens in the top shear box were measured after the drying process of drying-wetting cycle, wetting process of drying-wetting cycle, thermal cycle and drying cycle without heating, respectively. The measurement results shown that the falling magnitudes of soil moisture content during the drying process of drying-wetting cycle and drying cycle without heating, respectively, were almost the same, with about 40 % and 30 % less than the moisture contents of the Mercia Mudstone Clay and Kaolin Clay specimens before experiencing drying process of drying-wetting cycle and drying cycle without heating, respectively. Also, it was found that the moisture contents of clay samples after thermal cycle and the wetting process of drying-wetting cycle were almost the same with the moisture contents of the clay samples before experiencing thermal cycle and wetting process of drying-wetting cycle, respectively.

2.4.2 Creep shear tests

Creep shear tests were conducted under constant normal stress of 25 kPa (representative of approximately 1.25 m of cover soils) and was taken at the middle stress range of those for the rapid loading tests and a value typical in the UK practice when allowing for top soil and vegetation. For all the creep tests, initially, 24 hours consolidation was conducted, and then weights were added to the hanger until reaching the target creep shear stress. A detailed introduction of the creep tests is as follows:

(1) Creep tests subjected to drying-wetting cycles: In the tests, five different levels of creep shear stress: 80 %, 70 %, 60 %, 50 %, and 40 % of the peak shear strength for Kaolin Clay-GDL interfaces were adopted. The peak shear strength of Kaolin Clay-GDL interfaces (10.11 kPa) was determined by the standard rapid loading shear tests under 25 kPa normal stress. During the creep tests, initially, the interfaces were imposed by corresponding creep shear stress with being submerged into water. If the horizontal displacement of clayey soil-GDL interfaces had not reached the maximum value (80 mm) after 4 days from

imposing the creep shear stress, drying and wetting cycles were imposed on the interfaces. The drying process was conducted before the subsequent wetting process. During the drying process, water in the external shear box was discharged, and the heating system was turned on to dry the interfaces at a constant temperature of 40 ℃ for 24 hours. During the wetting process, the interfaces were fully submerged into water for 24 hours at the room temperature (22℃). This is one drying-wetting cycle. In this research, three drying-wetting cycles were conducted for each test.

(2) Creep tests subjected to thermal cycles: In the tests, two different creep shear stress levels of 70 % and 80 % of the peak shear strength for Kaolin Clay-GDL interfaces were adopted. The procedure of the creep tests subjected to thermal cycles was almost the same with the creep tests subjected to drying-wetting cycles, except that, unlike the drying cycles, during the heating cycles, the interfaces were heated to 40 ℃ whilst being submerged into water. In this research, three thermal cycles were conducted for each test.

(3) Creep tests subjected to drying-wetting cycles without heating: In the tests, the creep shear stress level 60 % of the peak shear strength for Kaolin Clay-GDL interfaces were adopted. The procedure of the creep tests subjected to drying-wetting cycles without heating was almost the same with the creep tests during drying-wetting cycles with heating, except that during the drying cycle without heating, only water in the external shear box was discharged, and the heating system was kept off to dry the interfaces at the room temperature of 22 ℃ for 7 days. In this case, one drying-wetting cycle without heating was carried out

for each test.

3 Results and analysis

3.1 Rapid loading shear tests

3.1.1 Impacts of temperature

Relationship curves between horizontal displacement of Kaolin Clay -GDL interfaces at different temperatures against shear stress are drawn in Figure 2. The corresponding curves of Mercia Mudstone Clay-GDL interfaces refer Figure 10 in Chao and Fowmes (2021). The detailed description of the shear displacement of Mercia Mudstone Clay-GDL interfaces under different temperature also refers to the first paper of the two-paper set (Chao and Fowmes, 2021)

Based on Figure 2, similar to Mercia Mudstone Clay-GDL interfaces, the horizontal displacement of Kaolin Clay-GDL interfaces at elevated temperature is higher than that at room temperature. Moreover, as with Mercia Mudstone Clay-GDL interfaces, with the rise of temperature, the peak shear strength of Kaolin Clay-GDL interfaces decreases, and the decreasing magnitude under low normal stress is larger than that under high normal stress. However, the falling amplitude of Kaolin Clay-GDL interfaces was lower than that of Mercia Mudstone Clay-GDL interfaces. For example, under 50 kPa normal stress, for Kaolin Clay-GDL interfaces, with the rise in temperature, the peak shear strength falls by 2.13 %. Meanwhile, for Mercia Mudstone Clay-GDL interfaces, the value is 5.49 %. Furthermore, similar to Mercia Mudstone Clay-GDL interfaces, the peak shear strength of Kaolin Clay-GDL interfaces at elevated temperature is more sensitive to the rise in normal stress than those at room temperature. For instance, when normal stress is increased from 15 kPa to 50 kPa, the peak shear strength of Kaolin Clay-GDL interfaces at room temperature increases by 135.10 %. Meanwhile, for the specimens at elevated temperature, the value is 436.30 %.

3.1.2 Impacts of drying-wetting cycles

The relationship curves between horizontal displacement of Mercia Mudstone Clay/ Kaolin Clay-GDL interfaces subjected to drying-wetting cycles against shear stress are drawn in Figure 3.

Based on Figure 3 (a), the horizontal displacement of Mercia Mudstone Clay-GDL interfaces with a high number of drying-wetting cycles is higher than those with a low number. More specifically, the difference between them increases gradually with the increase in shear stress. Taking the specimens under 50 kPa normal stress as an example, when the shear stress is 1.52 kN/m^2, the horizontal displacement for the specimen subjected to 3 drying-wetting cycles is 37.14 % and 81.75 % higher than those of specimens subjected to 1 and 0 cycle, respectively. In comparison, when shear stress is 2.21 kN/m^2, these values are 58.62 % and 97.54 %, respectively. Moreover, during drying-wetting cycles, the peak shear strength of the specimens gradually decreases. The extent of this decline under low normal stress is larger than that under high normal stress. This is presented in Figure 4 (a). For example, under 25 kPa normal stress, the peak shear strength of original Mercia Mudstone Clay-GDL interfaces falls by 11.91 % and 38.55 % when subjected to 1 and 3 drying-wetting cycles, respectively. In comparison, under 50 kPa normal stress, these values are 5.83 % and 8.45 % when subjected to 1 and 3 cycles, respectively. Furthermore, the impact of normal stress on the peak shear strength of the specimens subjected to drying-wetting cycles is larger than that of the original specimens. For instance, when normal stress is increased from

15 kPa to 50 kPa, the peak shear strength of the original specimens increases by 181 %, whilst for the specimens subjected to 3 cycles, the values is 523 % .

Based on Figure 3 (b), similar to Mercia Mudstone Clay-GDL interfaces, the horizontal displacement of Kaolin Clay-GDL interfaces with a high number of drying-wetting cycles is higher than those of a low number. However, unlike Mercia Mudstone Clay-GDL interfaces, the difference between the horizontal displacement of Kaolin Clay-GDL interfaces with a high number of drying-wetting cycles and those with a low number does not rise markedly with the increase in shear stress. Taking the specimens under 50 kPa normal stress as an example, when shear stress is 0.90 kN/m^2, the horizontal displacement for the specimen subjected to 3 drying-wetting cycles is 1.14 % and 1.5 % higher than those subjected to 1 and 0 cycle, respectively. In comparison, when shear stress is 1.32 kN/m^2, these values are 1.62 % and 1.94 %, respectively. Moreover, as with Mercia Mudstone Clay-GDL interfaces, the peak shear strength of Kaolin Clay-GDL interfaces decrease gradually during drying-wetting cycles. The extent of this decrease under low normal stress is larger than that of under high normal stress, as shown in Figure 4 (b). However, compared to Mercia Mudstone Clay-GDL interfaces, the falling amplitude of Kaolin Clay-GDL interfaces is lower. For example, under 25 kPa normal stress, the peak shear strength of original Kaolin Clay-GDL interfaces falls by 10.11 % and 13.33 % after 1 and 3 drying-wetting cycles, respectively. In comparison, for Mercia Mudstone Clay-GDL interfaces, these values are 11.91 % and 38.55 % after 1 and 3 cycles, respectively. Furthermore, similar to Mercia Mudstone Clay-GDL interfaces, the peak shear strength of Kaolin Clay-GDL interfaces subjected to drying-wetting cycles is more sensitive to the rise in normal stress than that of original specimens.

3.1.3 Impacts of thermal cycle

Relationship curves between horizontal displacement of Mercia Mudstone Clay/ Kaolin Clay -GDL interfaces during thermal cycles against shear stress are drawn in Figure 5.

Based on Figure 5 (a), the horizontal displacement of Mercia Mudstone Clay-GDL interfaces subjected to 1 thermal cycle is higher than that of the original specimens but lower than those subjected to 1 drying-wetting cycle. Moreover, during the thermal cycle, the decline in peak shear strength was observed. The decreasing amplitudes are lower than those during 1 drying-wetting cycle, respectively, as shown in Figure 3. For instance, under 25 kPa normal stress, after 1 thermal cycle, the peak shear strength of Mercia Mudstone Clay-GDL interfaces falls by 7.85 %. Whilst after 1 drying-wetting cycle, the percentage is 11.91 %.

Based on Figure 5 (b), similar to Mercia Mudstone Clay-GDL interfaces, the horizontal displacement of Kaolin Clay-GDL interface subjected to 1 thermal cycle is lower than those subjected to 1 drying-wetting cycle and higher than that of the original specimens. Moreover, as with Mercia Mudstone Clay-GDL interfaces, during the thermal cycle, the decreasing amplitude of peak shear strength for Kaolin Clay-GDL interfaces is lower than that during 1 drying-wetting cycle. This is presented in Figure 4. However, the decreasing amplitudes of Kaolin Clay-GDL interfaces during the thermal cycle are lower than those of Mercia Mudstone Clay-GDL interfaces. For instance, under 50 kPa normal stress, for Kaolin Clay-GDL interfaces, the peak shear strength reduces by 1.42 %, whist for Mercia Mudstone Clay-GDL interfaces, the number is 4.43 %.

3.1.4 Impacts of drying-wetting cycle without heating

Relationship curves between horizontal displacement of Mercia Mudstone Clay/ Kaolin Clay -GDL interfaces during drying-wetting cycle without heating against shear stress are drawn in Figure 6.

Based on Figure 6 (a), the horizontal displacement of Mercia Mudstone Clay-GDL interfaces subjected to 1 drying-wetting cycle without heating is higher than that of the original specimen but lower than those subjected to 1 thermal cycle. Moreover, compared to the original specimen, the decrease in peak shear strength of the specimen subjected to 1 drying-wetting cycle without heating was observed. However, the decreasing amplitudes are lower than those that are subjected to 1 drying-wetting cycle with heating and 1 thermal cycle, respectively. For instance, under 25 kPa normal stress, after 1 thermal cycle, the peak shear strength of Mercia Mudstone Clay-GDL interfaces falls by 7.85 %. Meanwhile, after 1 drying-wetting cycle without heating, the value is 3.74 %. This indicates that the impacts of drying alone on the peak shear strength of Mercia Mudstone Clay-GDL interfaces is small, which is lower than those of sole heating and drying with heating, respectively.

Based on Figure 6 (b), similar to Mercia Mudstone Clay-GDL interfaces, the horizontal displacement of Kaolin Clay-GDL interfaces subjected to 1 drying-wetting cycle without heating is higher than that of the original specimen but lower than those subjected to 1 thermal cycle. Moreover, as with Mercia Mudstone Clay-GDL interfaces, compared with the original specimen, the decrease in peak shear strength of the Kaolin Clay-GDL interface subjected to 1 drying-wetting cycle without heating was observed. However, the decreasing amplitudes are lower than those of the specimens subjected to

1 drying-wetting cycle with heating and 1 thermal cycle, respectively. This indicates that the impacts of drying alone on the peak shear strength of Kaolin Clay-GDL interfaces is small, which is lower than those of sole heating and drying with heating, respectively. Additionally, the decreasing amplitudes of peak shear strength of Kaolin Clay-GDL interfaces during drying-wetting cycle without heating are lower than those of Mercia Mudstone Clay-GDL interfaces, respectively. For instance, under 25 kPa normal stress, for Kaolin Clay-GDL interfaces, the peak shear strength reduces by 3.5 %, whilst, for Mercia Mudstone Clay-GDL interfaces, the figure is 3.74 %.

3.2 Creep shear tests

3.2.1 Impacts of creep shear level

Figure 7 presents the creep shear displacement of Kaolin Clay-GDL interfaces during the whole test. The corresponding curves of Mercia Mudstone Clay-GDL interfaces refer Figure 13 in Chao and Fowmes (2021). The detailed description of the creep deformation of Mercia Mudstone Clay-GDL interfaces under different creep shear stress levels also refers to the first paper of the two-paper set (Chao and Fowmes, 2021).

Based on Figure 7, similar to Mercia Mudstone Clay-GDL interfaces, the level of creep shear stress has significant impacts on the creep shear deformation of Kaolin Clay-GDL interfaces. The horizontal displacement of Kaolin Clay-GDL interfaces under a high creep shear stress level is higher than those under a low shear stress level. Especially for the Kaolin Clay-GDL interface under 80 % creep shear stress level, the sample fails before the beginning of drying-wetting cycles. In comparison, the Mercia Mudstone Clay-GDL interface remains stable under the 90 % creep shear stress level before the beginning of drying-wetting cycles. When the creep shear stress level is lower than or equal to 70 %, the interfaces become stable after the primary creep stage. Additionally, as with Mercia Mudstone Clay-GDL interfaces, the influence of drying-wetting cycles on the creep displacement of Kaolin Clay-GDL interfaces are large. The impacts are more evident for interfaces under a high creep shear stress level than those under a low creep shear stress level. For example, during the first drying cycle, the horizontal displacement of the interface under 40 % creep shear stress level rises around 0.6 mm, whilst that under 60 % creep shear stress level rises about 2.5 mm. Especially for the interface under 70 % creep shear stress level, it comes to failure caused by the first drying cycle. In comparison, for Mercia Mudstone Clay-GDL interfaces, failure does not occur during the drying-wetting cycles when the creep shear stress level is less than or equal to 70 %.

3.2.2 Impacts of drying-wetting cycles

To further analyse the impact of drying-wetting cycles on creep deformation of the interfaces, taking the beginning time of the first drying cycle as the 0 minute and the horizontal displacement at the beginning of the first drying cycle as 0 mm, curves about horizontal displacement of Kaolin Clay-GDL interfaces under 60 %, 50 % and 40 % creep shear stress levels in elapsed time are drawn in Figure 8. The corresponding curves of Mercia Mudstone Clay-GDL interfaces under 70 %, 60 % and 50 % creep shear stress levels refer Figure 15 in Chao and Fowmes (2021). The detailed description of the creep deformation of Mercia Mudstone Clay-GDL interfaces during drying-wetting cycles also refers to Chao and Fowmes (2021) .

Based on Figure 8, as with Mercia Mudstone Clay-GDL interfaces, the first drying cycle and wetting cycle have the highest influence over the horizontal displacement of

Kaolin Clay-GDL interfaces compared with the following drying and wetting cycles, respectively. Taking the Kaolin Clay-GDL interface under 60 % creep shear stress level as an example, the horizontal displacement rises by 1.5 mm and 1.4 mm during the first drying and first wetting cycle, respectively. Meanwhile, during the third drying cycle and wetting cycle, the value is 0.6 mm and 0.3 mm, respectively. Additionally, as with Mercia Mudstone Clay-GDL interfaces, the impact of drying cycles on the horizontal displacement of Kaolin Clay-GDL interfaces is larger than that of wetting cycles. However, compared to Mercia Mudstone Clay-GDL interfaces, wetting cycles have greater impacts on the creep deformation of Kaolin Clay-GDL interfaces. For the drying cycles, the opposite phenomenon is observed. For instance, under 50 % creep shear stress level, the horizontal displacement of Kaolin Clay-GDL interfaces increases about 2 mm during the first drying cycle, whereas this is 4.6 mm for Mercia Mudstone Clay-GDL interfaces. In comparison, during the first wetting cycle, the horizontal displacement of Mercia Mudstone Clay-GDL interfaces and Kaolin Clay-GDL interfaces rises by 0.34 mm and 1.37 mm, respectively.

3.2.3 Impacts of thermal cycles

The experimental results of the creep tests on Kaolin Clay-GDL interfaces subjected to thermal cycles and the creep tests subjected to drying-wetting cycles under the same creep shear stress level are plotted in Figure 9. The corresponding curves of Mercia Mudstone Clay-GDL interfaces during thermal cycles refer Figure 16 in Chao and Fowmes (2021). In order to further determine that, during the drying cycles, the increase in creep shear displacement of Clayey soil-GDL interfaces is due to the combined impacts of elevated temperature and drying or the individual impact of the two factors, taking the beginning time of the first drying/thermal cycle as the 0 minute and the horizontal displacement at the beginning of the first drying/thermal cycle as 0 mm, the horizontal displacement of Kaolin Clay-GDL interfaces subjected to thermal cycles and subjected to drying-wetting cycles under 60 % creep shear stress level in elapsed time was drawn in Figure 10, respectively. The corresponding curves of Mercia Mudstone Clay-GDL interfaces under 70 %, creep shear stress levels refer Figure 17 in Chao and Fowmes (2021). The detailed description of the creep deformation of Mercia Mudstone Clay-GDL interfaces during thermal cycles also refers to Chao and Fowmes (2021).

Based on Figure 9, similar to Mercia Mudstone Clay-GDL interfaces, the horizontal displacement of Kaolin Clay-GDL interfaces increases markedly during the first thermal cycle. Especially for the Kaolin Clay-GDL interface under 70 % creep shear stress level, failure occurs in the first thermal cycle. However, for the Mercia Mudstone Clay-GDL interface at the same creep shear stress level, failure does not occur during the first thermal cycle. Regarding the Kaolin Clay-GDL interface under 60 % creep shear stress level, the first thermal cycle has the highest influence on the horizontal displacement. For example, during the first thermal cycle, the horizontal displacement rises by around 2.9 mm, whereas during the third thermal cycle, this is about 1 mm. This demonstrates that elevated temperature is an important factor to result in the rise in the horizontal displacement of Kaolin Clay-GDL interfaces during creep deformation.

Based on Figure 10, similar to Mercia Mudstone Clay-GDL interfaces, the rise in horizontal displacement of Kaolin Clay-GDL interfaces during the thermal cycles is always higher than those during the drying cycles. This can be attributed to the fact that during thermal cycles, the Kaolin Clay-GDL interfaces were submerged in water. This softened the overlaying clay sample to provide more lubrication between Kaolin Clay particles and Kaolin Clay - GDL interfaces, respectively, reducing the shear resistance of Kaolin Clay-GDL interfaces. In comparison, during the drying cycles, the overlaying clay sample was unsaturated. This led to the generation of suction in soil to enhance the shear resistance of Kaolin Clay-GDL interfaces. For example, during the first thermal cycle, the horizontal displacement rises by 2.9 mm, which is around 1.4 mm higher than that during the first drying cycle.

3.2.4 Impacts of drying cycles without heating

The experimental results of the creep tests on Kaolin Clay-GDL interfaces subjected to drying-wetting cycle without heating under the creep shear stress level of 60 % and the corresponding creep tests subjected to drying-wetting cycles and thermal cycles under the same creep shear stress level were plotted in Figure 11. The corresponding curves of Mercia Mudstone Clay-GDL interfaces under 70 %, creep shear stress levels refer Figure 18 in Chao and Fowmes (2021). In order to further determine that, during drying cycles with heating, the increase in creep shear displacement of Clayey soil-GDL interfaces is due to the combined impacts of elevated temperature and drying, or individual impacts of the two factors, taking the beginning time of the first drying cycle without heating, drying cycle with heating and thermal cycle as the 0 minute, respectively, and the horizontal displacement at the beginning of the first drying cycle without heating, drying cycle with heating and the thermal cycle as 0 mm, the horizontal displacement of Kaolin Clay-GDL interfaces subjected to drying-wetting cycle without heating under the creep shear stress level of 60 % and the creep tests subjected to drying-wetting cycles with heating and thermal cycles under the same creep shear stress level in elapsed time was drawn in Figure 12. The corresponding curves of Mercia

Mudstone Clay-GDL interfaces under 70 %, creep shear stress levels refer Figure 17 in Chao and Fowmes (2021). The detailed description of the creep deformation of Mercia Mudstone Clay-GDL interfaces during drying-wetting cycle without heating also refers to Chao and Fowmes (2021).

Based on Figure 11, as with Mercia Mudstone Clay-GDL interfaces, for the Kaolin Clay-GDL interface subjected to drying-wetting cycle without heating, its horizontal displacement keeps stable during the drying cycle without heating. Variation in the horizontal displacement of the interfaces during the drying cycles with heating and during the heating processes of thermal cycles is significantly higher than that during the drying cycle without heating.

Based on Figure 12, similar to Mercia Mudstone Clay-GDL interfaces, the rise in horizontal displacement of Kaolin Clay-GDL interfaces during the drying cycle without heating is significantly lower than those during the drying cycles with heating and the heating processes of thermal cycles. This can be related to the same mechanism as that for Mercia Mudstone Clay-GDL interfaces. Regarding the specific variation amplitude of horizontal displacement, the horizontal displacement rises by 0.3 mm during the drying cycle without heating, whilst this increase during the first heating process of thermal cycles and the first drying cycle with heating is 3.0 mm and 1.6 mm, respectively. This indicates that the impacts of drying alone on the rise in horizontal displacement of Kaolin Clay-GDL interfaces during drying cycles is marginal and that the main influence factor is elevated temperature.

4 Discussion

The peak shear strength and creep shear resistance of clayey soil-GDL interfaces is mobilised from two components: the skin friction between fibres of geotextile bonded on the drainage core of GDL and soil, and the interlocking effects between soil and cuspate elements on the drainage core of GDL (Bacas et al., 2015). In the first paper of the two paper-set (Chao and Fowmes, 2021), the decrease in peak shear strength and creep shear resistance of clayey soil-GDL interfaces at elevated temperature is ascribed to that, due to the presence of thermo-softening plastic materials, the stiffness (modulus) of HDPE drainage core and fibres of geotextiles bonded on the drainage core decreases at elevated temperature, which results in the softening of cuspate elements on the drainage core and the fibres of geotextiles (Hanson et al., 2015). The softening cuspate elements are easier to compress. This reduces the penetrating depth of the cuspate elements into soil, as they are easier to deform during the shearing process, weakening the interlocking effects between soil and GDL. Meanwhile, the softening fibres are easier to align during the shearing process to decrease the skin friction between soil and GDL.

In rapid loading shear tests, for the interfaces subjected to drying-wetting cycles and thermal cycles, in shearing process, when the temperature of interfaces decreases to the normal level again, although an increase can occur in the stiffness of drainage core, the compressive deformation of the cuspate elements on the drainage core caused by elevated temperature cannot recover fully (Karademir, 2011). It results in the small penetrating depth of the cuspate elements into soil, weakening the interlocking effects between soil and GDL.

It is noteworthy to mention that, actually, the temperature-related environmental loadings, including elevated temperature, drying-wetting cycles and thermal cycles, have two contradictory effects on the mechanical characteristics of interfaces. More specifically, as aforementioned, the elevated temperature can cause the softening of drainage core and geotextile fibre of GDL to weaken the interlocking effects and skin friction between soil and GDL, resulting in the decrease in the peak shear strength and creep shear resistance of interfaces. On the other hand, at elevated temperature, the softening drainage core and geotextile fibre are easier to be compressed under normal stress to result in larger contact area between soil and GDL than that at normal temperature to rise the skin fiction, leading in the increase in the peak shear strength and creep shear resistance of interfaces. Overall, the detrimental effects of elevated temperature on the peak shear strength and creep shear resistance of interfaces are higher than the enhancing effects. Thus, when the interfaces are subjected to temperature-related environmental loadings, including elevated temperature, drying-wetting cycles and thermal cycles, the peak shear strength and creep shear resistance of interfaces decreases.

The higher sensitivity of peak shear strength of interfaces to the temperature-related environmental loadings, including elevated temperature, drying-wetting cycles and thermal cycles, under low normal stress than those under high normal stress can be attributed to the aforementioned two contradictory effects of elevated temperature on the mechanical properties of interfaces. Under high normal stress, the rising contact area between soil and GDL due to the softening drainage core and geotextile fibre caused by elevated temperature is higher than that under low normal stress. The higher rising magnitude of contact area between soil and GDL can provide larger skin friction to improve the enhancing effects of elevated temperature on the peak shear strength and creep shear resistance of interfaces, which can offset more detrimental effects of elevated temperature on the mechanical properties of interfaces to reduce the decreasing magnitude of peak shear strength and creep shear resistance of interfaces when subjected to the temperature-related environmental loadings. Thus, under high normal stress, the peak shear strength of interfaces is less sensitive to the temperature-related environmental loadings than that under low normal stress.

To further analyse the interaction mechanism, consolidated undrained triaxial shear tests were conducted on the prepared Mercia Mudstone Clay and Kaolin Clay specimens subjected to the same process of drying-wetting cycles on clayey soil-GDL interfaces by being submerged into water for 24 hours to wet and placed in 40 °C temperature for 24 hours to dry. The obtained peak shear strength of the soil specimens were drawn in Figure 13 .Based on Figure 13, for both of Mercia Mudstone Clay and Kaolin Clay specimens, their peak shear strength reduces consistently during drying-wetting cycles, Thus, in rapid loading shear tests, when clayey soil-GDL interfaces were subjected to drying-wetting cycles, the reducing shear strength of clayey soil above GDL further weakens the interlocking effects between clayey soil and GDL, resulting in the larger decreasing amplitude of shear resistance for the interfaces subjected to one drying-wetting cycle than those subjected to one thermal cycle to cause the peak shear strength of the interfaces subjected to one drying-wetting cycle being lower than that subjected to one thermal cycle.

The reason that, in rapid loading shear tests, the peak shear strength of clayey soil-GDL interfaces subjected to a drying-wetting cycle without heating is slightly lower than that of original specimens but significantly higher than the interfaces subjected to drying-wetting cycles and thermal cycles, respectively, can be attributed to the fact that, in the absence of elevated temperatures, the stiffness of the drainage core and geotextile fibres of the interfaces subjected to drying-wetting cycles without heating is identical to that of original specimens during the tests. The aforementioned softening of the drainage core and weakening of the interlocking effects between clayey soil and GDL caused by the decrease in stiffness of the GDL drainage core does not occur in clayey soil-GDL interfaces subjected to drying-wetting cycle without heating. Only the impacts of drying-wetting cycles alone, which are mentioned in above paragraph are imposed on the short-term mechanical properties of clayey soil-GDL interfaces. This also indicates that the impacts of a drying-wetting cycle alone on the decrease in peak shear strength of clayey soil-GDL interfaces during drying-wetting cycles with heating is marginal, with the main influence factor being elevated temperature.

Another aspect which should be noted is that Mercia Mudstone Clay-GDL interfaces have higher peak shear strength and can keep stable under larger creep shear stress level than that of Kaolin Clay-GDL interfaces, which can be attributed to the stronger interlocking effects of Mercia Mudstone Clay-GDL interfaces than that of Kaolin-GDL interfaces, resulting from the larger peak shear strength of Mercia Mudstone Clay than that of Kaolin Clay. This is presented in Figure 13.

The larger influence of temperature-related environmental loadings, including elevated temperature, drying-wetting cycles and thermal cycles on the mechanical properties of Mercia Mudstone Clay-GDL interfaces than that of Kaolin Clay-GDL interfaces can be explained by the following content. As aforementioned, elevated temperature has two contradictory effects on the mechanical properties of interfaces. At elevated temperature, the enhancing effect of elevated temperature on the mechanical properties of interfaces is that the softening drainage core and geotextile fibre can result in larger contact area between soil and GDL to increase the skin friction, resulting in higher peak shear strength and creep shear resistance of interfaces. Since Kaolin Clay is more sticky than Mercia Mudstone Clay, with the same rising contact area, Kaolin Clay can stick to the surface of GDL more strongly to provide higher skin friction between Kaolin Clay and GDL than that between Mercia Mudstone Clay and GDL, resulting in larger enhancing effects of elevated temperature on the peak shear strength and creep shear resistance of Kaolin Clay-GDL interfaces than that of Mercia Mudstone Clay-GDL interfaces. The higher enhancing effects of elevated temperature on the mechanical properties of interfaces can offset more the detrimental effects of elevated temperature to reduce the decreasing magnitude of peak shear strength and creep shear resistance of interfaces when subjected to temperature-related environmental loadings. Thus, the decreasing extent of peak shear strength and increasing extent of creep horizontal displacement for Mercia Mudstone Clay-GDL interfaces are greater than those of Kaolin Clay–GDL interfaces under the impacts of the temperature-related environmental factors, respectively.

The higher influence of drying-wetting cycle without heating on the mechanical properties of Mercia Mudstone Clay-GDL interfaces than that of Kaolin Clay-GDL interfaces can be contributed to the greater reducing magnitude of peak shear strength of Mercia Mudstone Clay during drying-wetting cycles than that of Kaolin Clay, as presented in Figure 13. The greater reducing magnitude of peak shear strength for soil can cause the larger decreasing magnitude of interlocking effects between soil and GDL to result in the larger decreasing magnitude of peak shear strength and creep shear resistance of interfaces. Therefore, during drying-wetting cycle without heating, the decreasing extent of peak shear strength and increasing extent of creep horizontal displacement for Mercia Mudstone Clay-GDL interfaces are higher than those of Kaolin Clay-GDL interfaces, respectively.

5 Conclusion

In this paper, a series of rapid loading shear tests and creep shear tests were conducted on different kinds of clayey soil-GDL interfaces subjected to environmental loadings using the self-designed temperature and stress-controlled large direct shear apparatus. Based on the experimental results, the impacts of drying-wetting cycles, thermal cycles and elevated temperature, etc. on the short-term and creep mechanical characteristics of different kinds of clayey soil-GDL interfaces were investigated. The main conclusions are summarised as follows:

(1) Under low normal stress, the peak shear strength of clayey soil-GDL interfaces is more sensitive to drying-wetting cycles and elevated temperature than those under high normal stress. This can be attributed to that, under high normal stress, the rising contact area between soil and GDL due to the softening drainage core and geotextile fibre caused by elevated temperature is higher than that under low normal stress, which can provide larger skin friction to improve the enhancing effects of elevated temperature on the peak shear strength and creep shear resistance of interfaces to offset more detrimental effects of elevated temperature, resulting in the reduction of the decreasing magnitude of peak shear strength and creep shear resistance of interfaces when subjected to the temperature-related environmental loadings.

(2) Compared with the original specimens, the interfaces subjected to drying-wetting cycles, thermal cycles and elevated temperature, have lower peak shear strength and creep shear resistance, For example, under 25 kPa normal stress, the peak shear strength of original Mercia Mudstone Clay-GDL interfaces falls by 38.55 % and 13.33%, respectively, when subjected to 3 drying-wetting cycles. This can be ascribed to the weakening of interlocking effects and skin friction between soil and GDL caused by the softening of drainage core and geotextile fibers of GDL and the decline in the peak shear strength of soil.

(3) Owing to the larger peak shear strength of Mercia Mudstone Clay than that of Kaolin Clay, the peak shear strength and creep shear resistance of Mercia Mudstone Clay-GDL interfaces is higher than that of Kaolin Clay-GDL interfaces. Additionally, the larger detrimental influence of temperature-related environmental loadings on the peak shear strength and creep shear resistance of Mercia Mudstone Clay-GDL interfaces than those of Kaolin Clay-GDL interfaces can be attributed to that the enhancing effects of elevated temperature on the mechanical properties of Kaolin Clay-GDL interfaces are higher than those of Mercia Mudstone Clay-GDL interfaces to offset more the detrimental effects of elevated temperature, resulting in the reduction of the decreasing magnitude of peak shear strength and creep shear resistance of Kaolin Clay-GDL interfaces when subjected to temperature-related environmental loadings.

(4) The peak shear strength of the clayey soil-GDL interfaces subjected to one drying-wetting cycle is lower than that subjected to one thermal cycle because

of the reduction in the peak shear strength of clayey soil above GDL during drying-wetting cycles.

(5) The rise in creep displacement of the clayey soil-GDL interfaces during thermal cycles is higher than that during drying cycle with heating because during thermal cycles, the interfaces were submerged by water to soften the overlaying soil to reduce the shear resistance between soil and GDL.

(6) The decreasing magnitude of peak shear strength and increasing magnitude of creep displacement for the interfaces subjected to drying-wetting cycle without heating is significantly lower than that subjected to drying cycle with heating /thermal cycle, respectively. It indicates that the impacts of drying alone on the decrease in the peak shear strength and creep shear resistance of clayey soil-GDL interfaces during drying cycles with heating is small, and the main influence factor is the elevated temperature.

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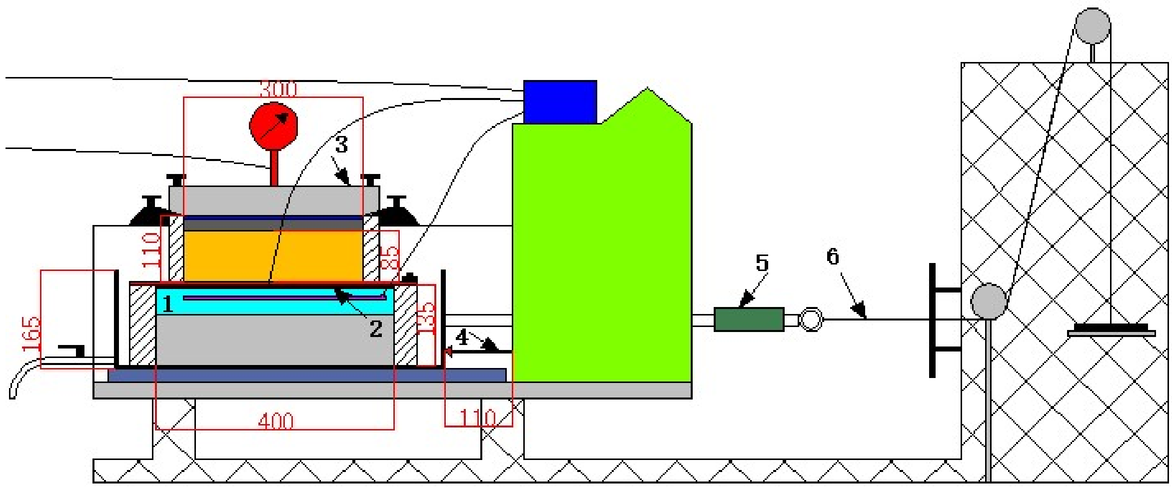


1. Aluminium heating plate 2. Pyramid teeth gripping plate 3. Air pressure bladder 4. Horizontal movement transducer 5. Load cell 6. Steel wire

Figure 1 The schematic diagram of the developed apparatus

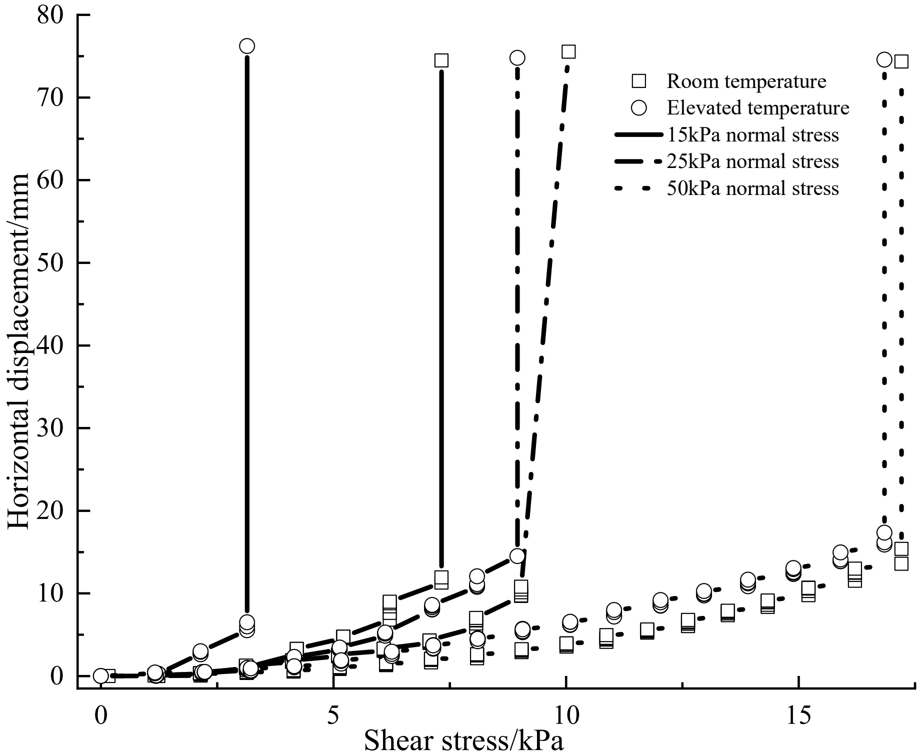
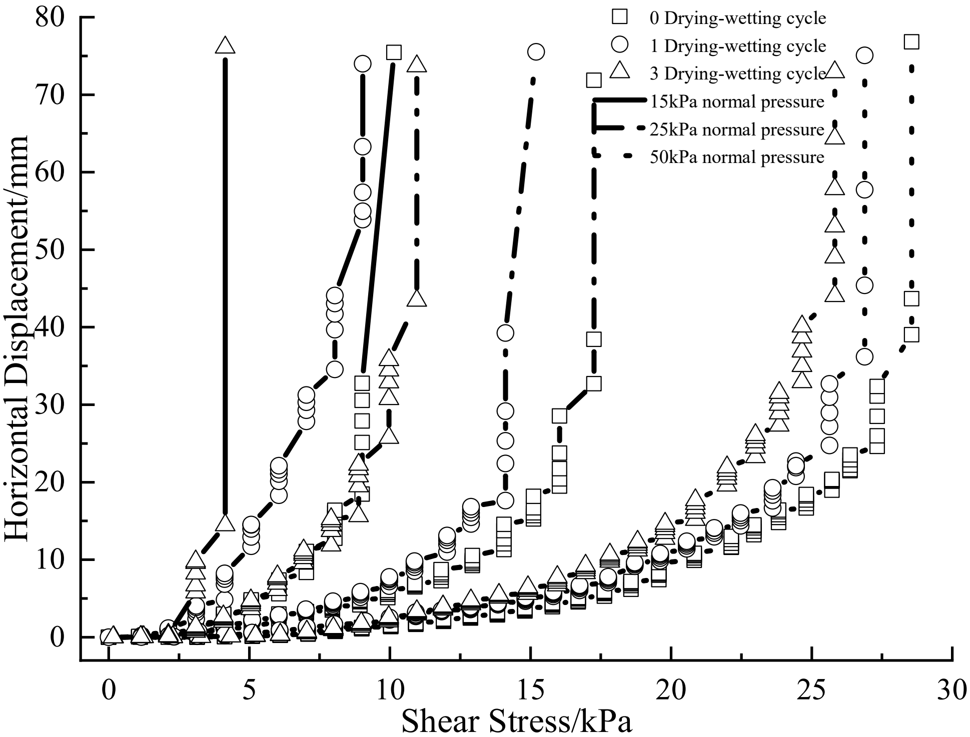
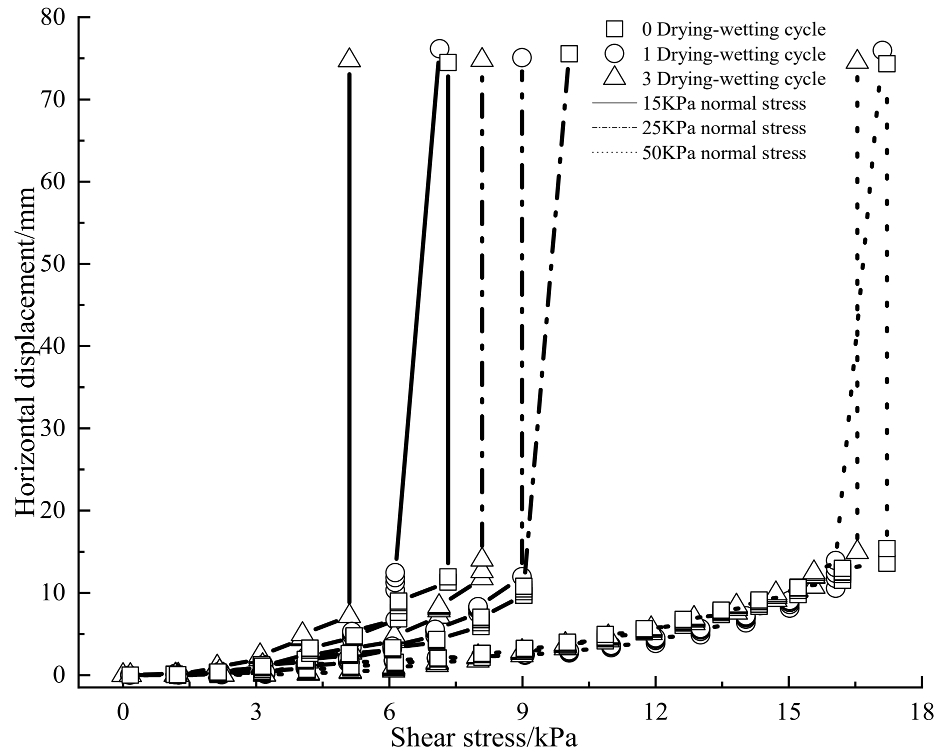


Figure 2 Shear stress-horizontal displacement curves of Kaolin Clay-GDL interfaces at different temperatures

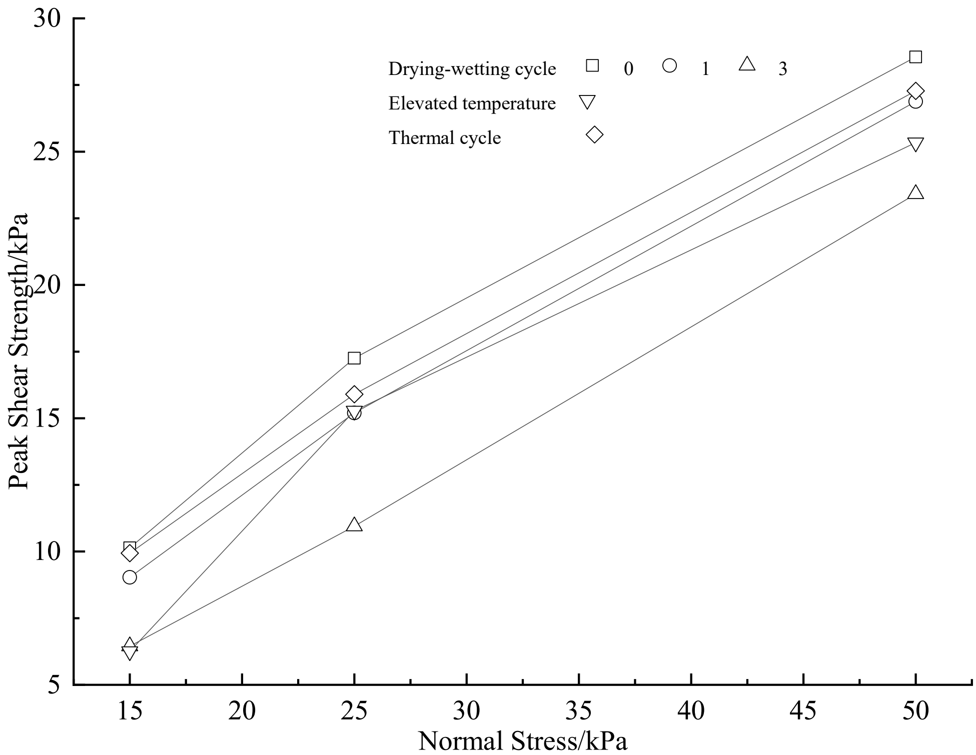


(a)Kaolin Clay-GDL interfaces

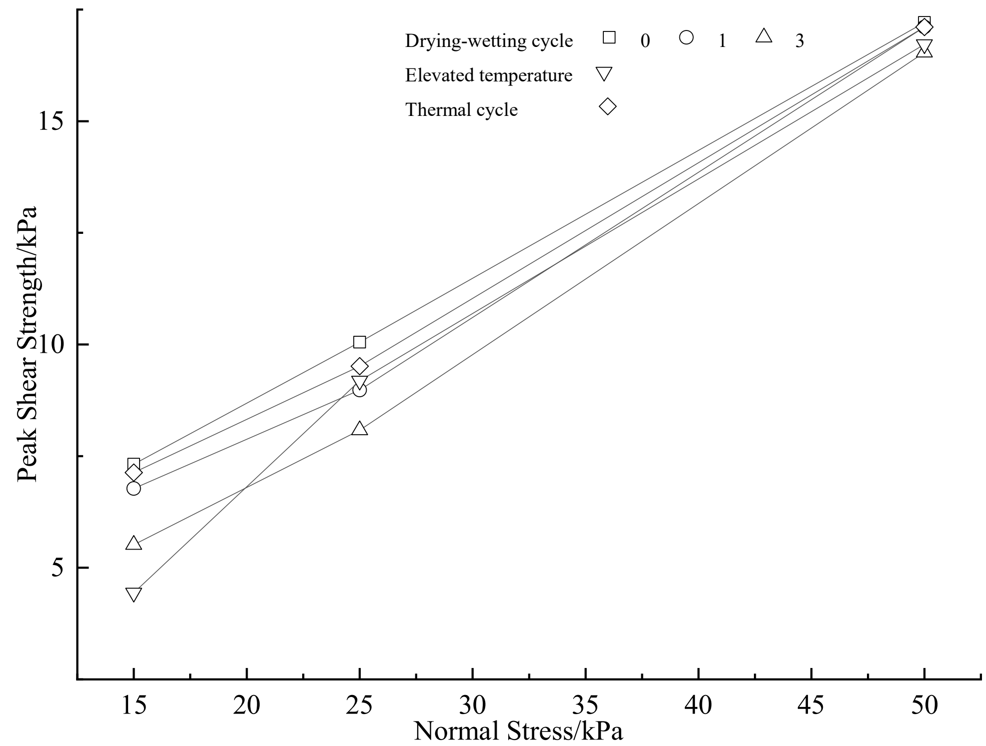


(b)Mercia Mudstone Clay-GDL interfaces

Figure 3 Tests on interfaces subjected to different drying-wetting cycles



(a)Mercia Mudstone Clay-GDL interfaces



(b) Kaolin Clay-GDL interfaces

Figure 4 The peak shear strength of clayey soil-GDL interfaces

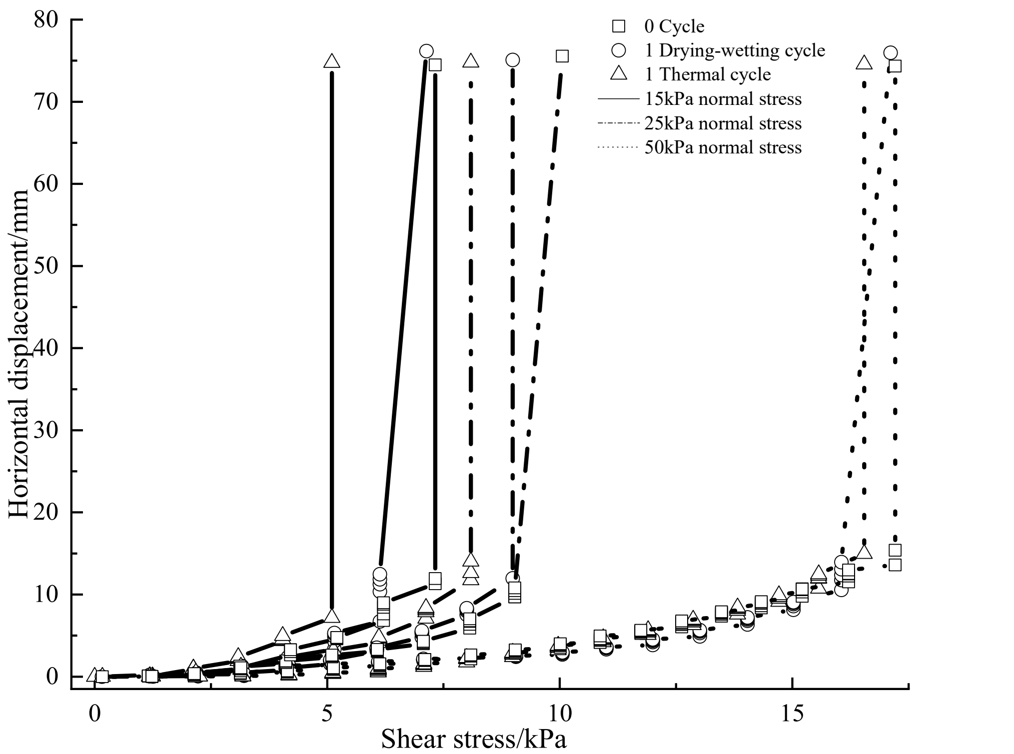
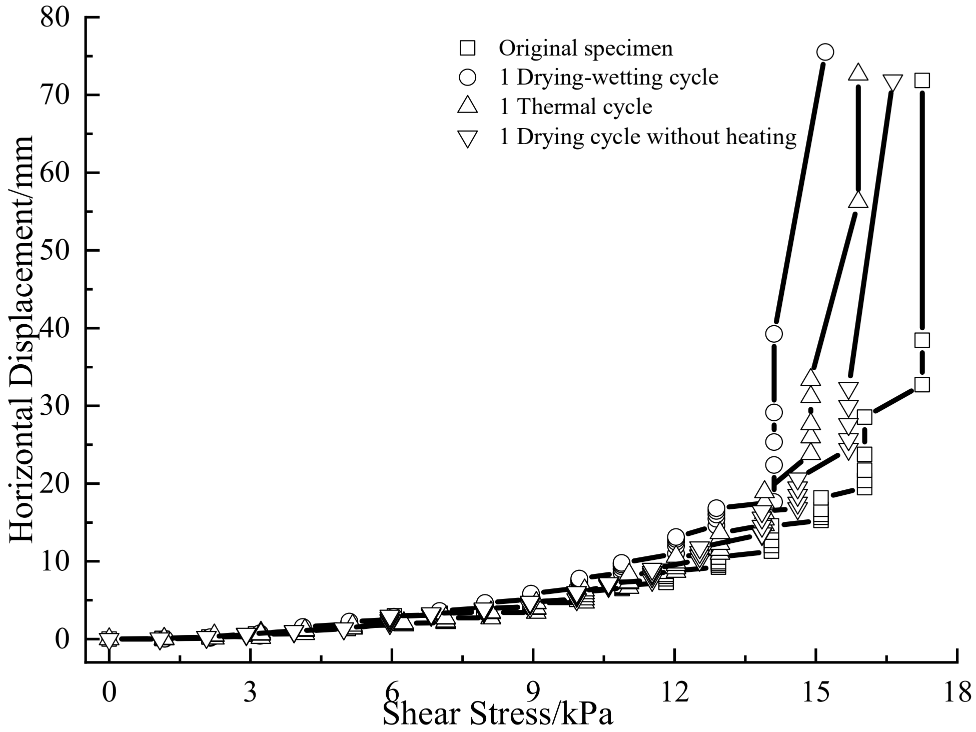
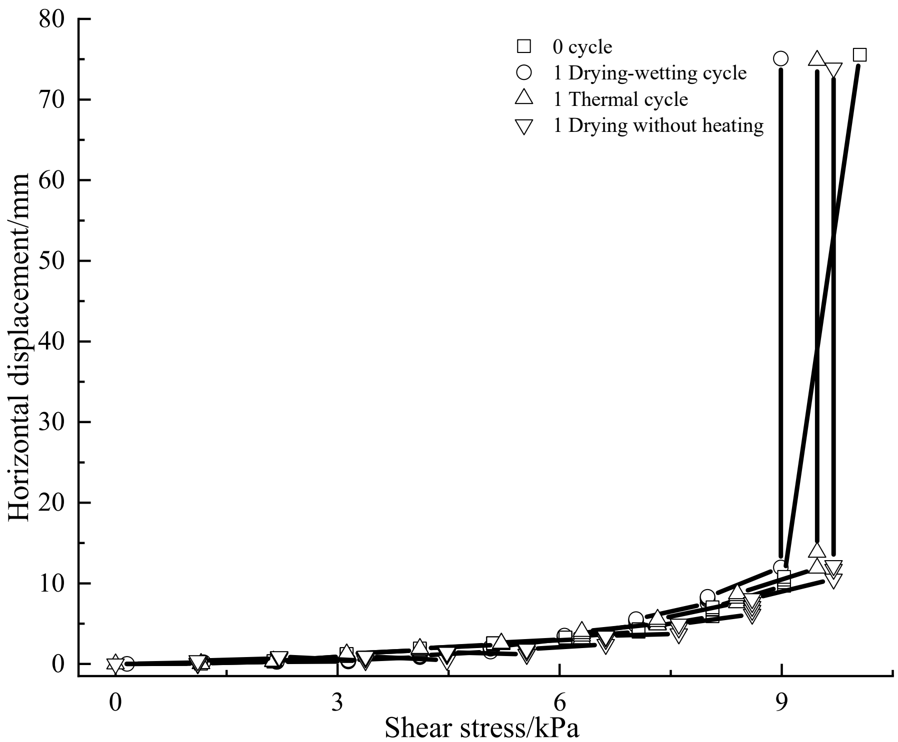


Figure 5 Shear stress-horizontal displacement curves of Kaolin Clay-GDL interfaces

subjected to thermal cycle



(a) Mercia Mudstone Clay-GDL interfaces



(b) Kaolin Clay-GDL interfaces

Figure 6 Tests on interfaces subjected to drying cycle without heating under 25 kPa normal stress

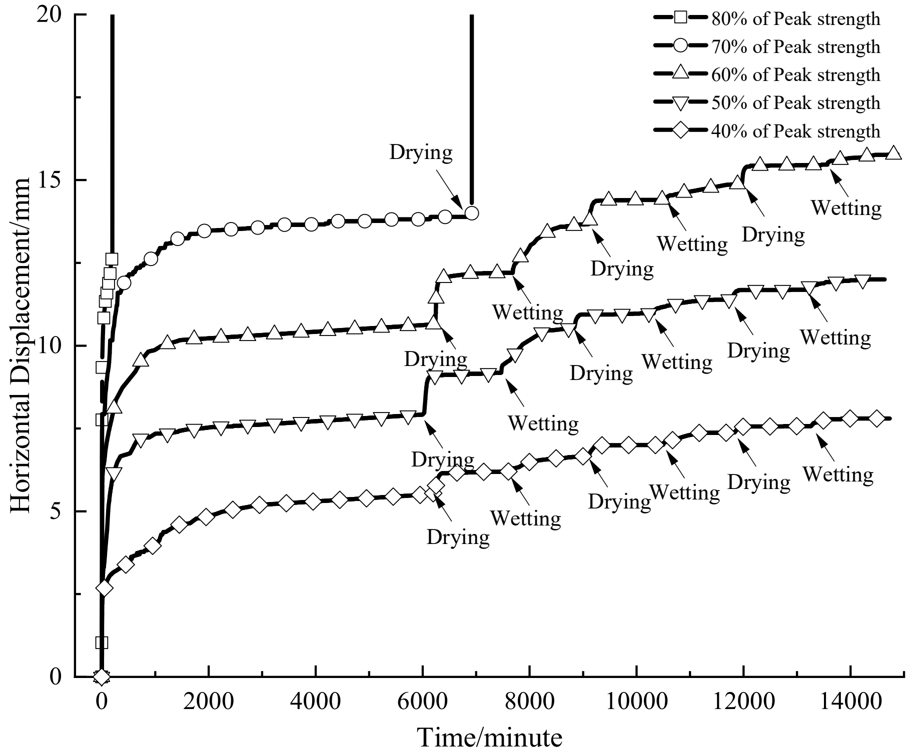


Figure 7 The shear creep deformation of Kaolin Clay-GDL interfaces during the whole test

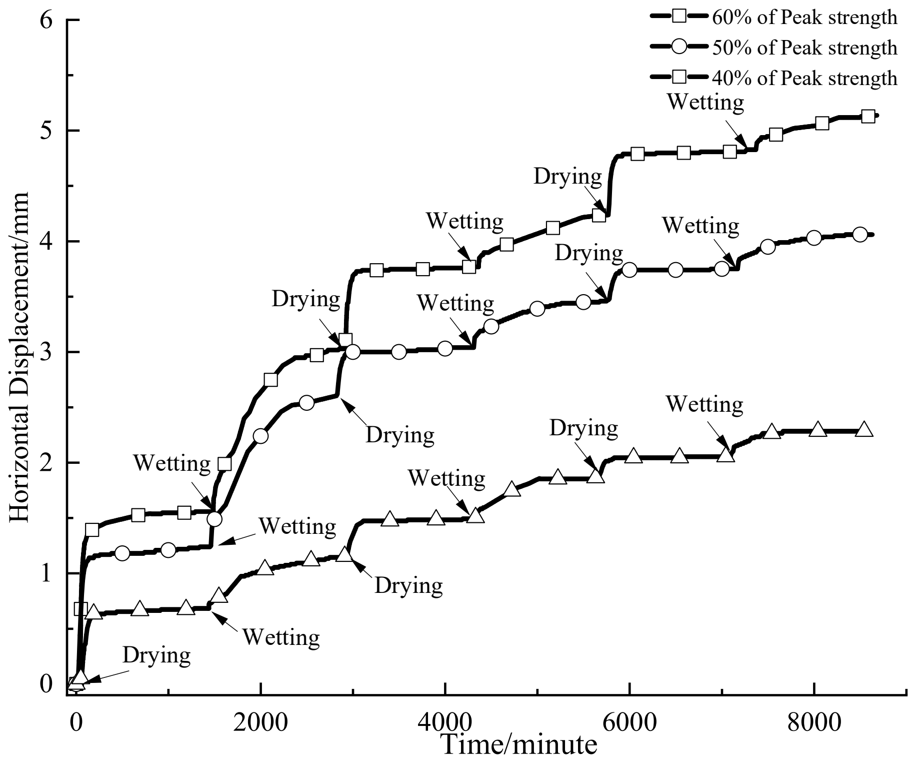


Figure 8 The creep shear displacement of Kaolin Clay-GDL interfaces during drying-wetting cycles

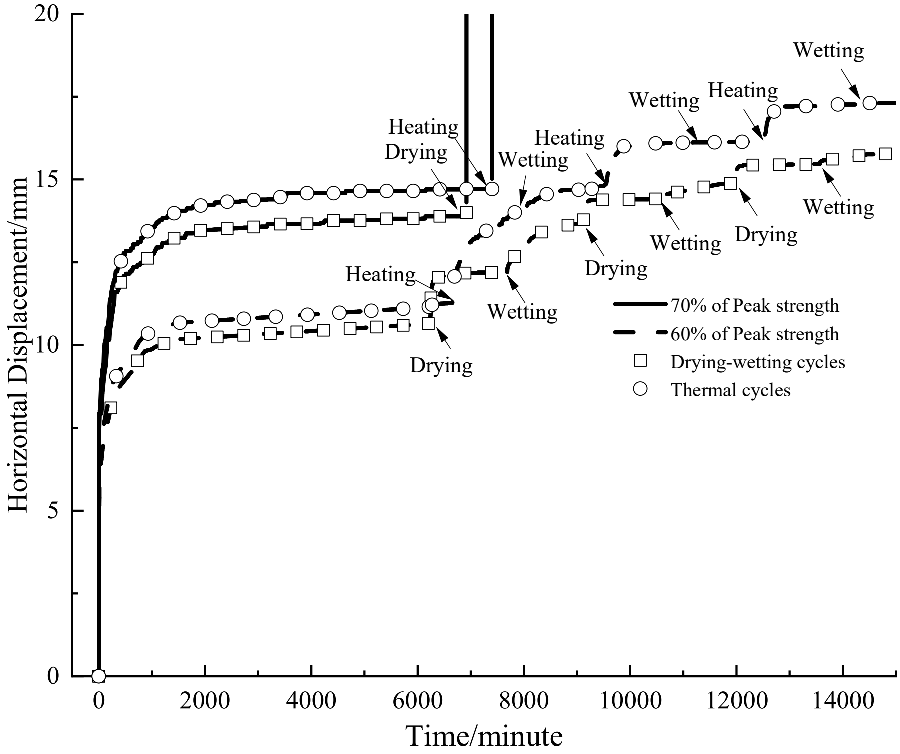


Figure 9 The influence of thermal cycles on creep behaviour of Kaolin Clay-GDL interfaces during the whole tests

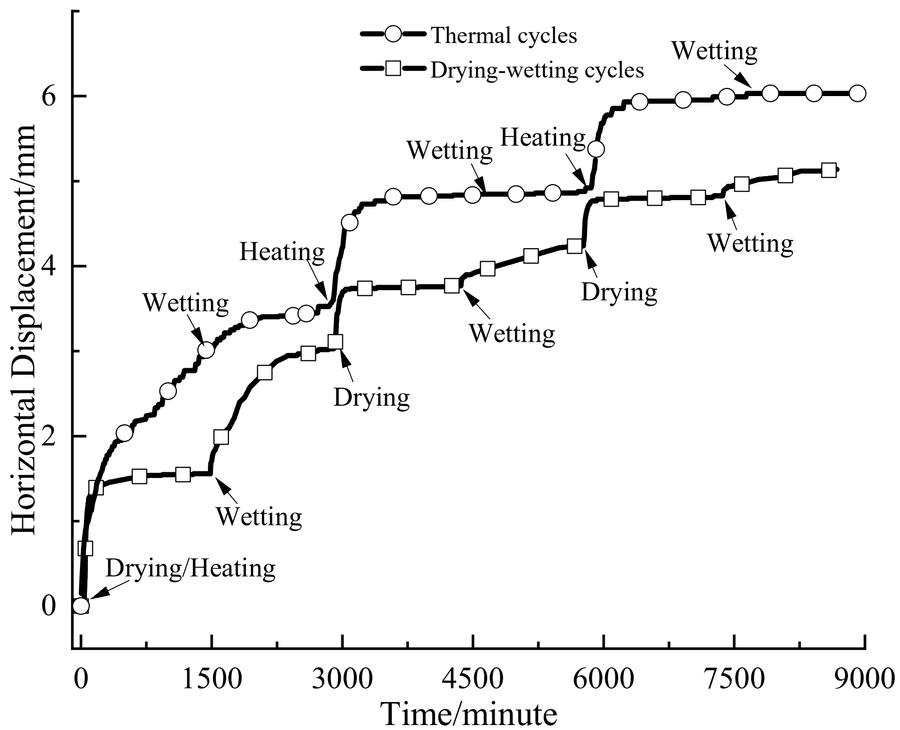


Figure 10 The impacts of thermal cycles on creep deformation of Kaolin Clay-GDL interfaces during drying-wetting/thermal cycles

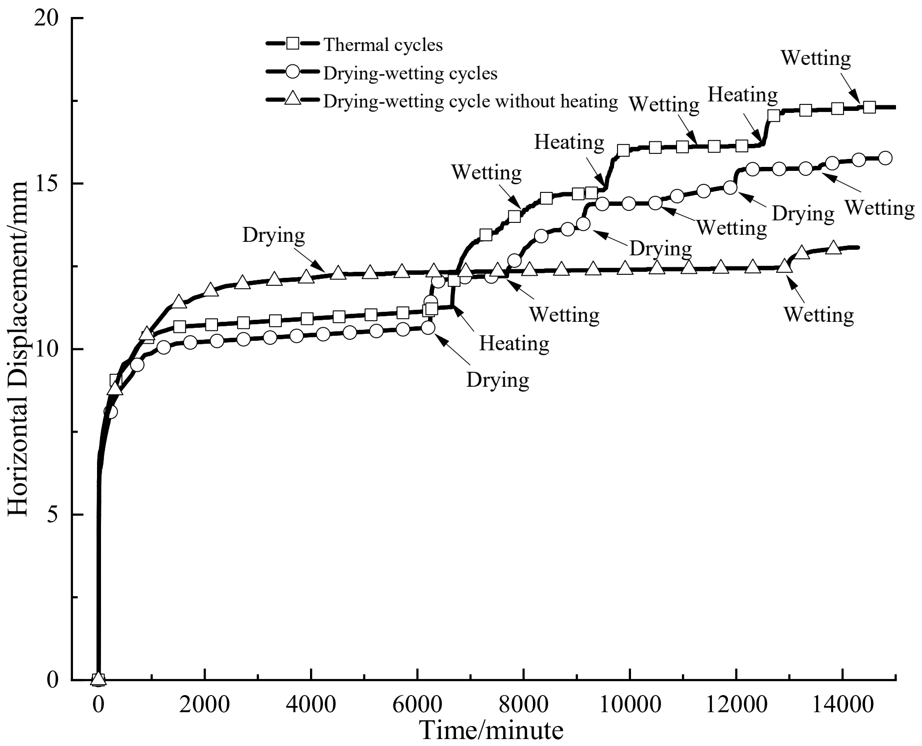


Figure 11 The influence of drying-wetting cycle without heating on creep behaviour of Kaolin Clay-GDL interfaces during the whole tests

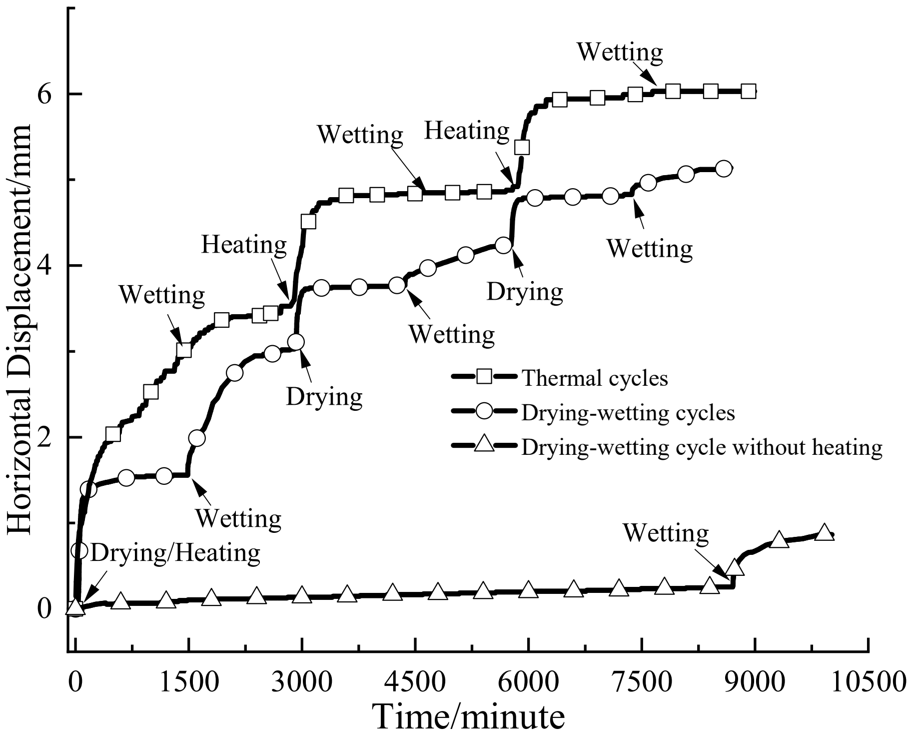


Figure 12 The impacts of drying-wetting cycle without heating on creep deformation of Kaolin Clay-GDL interfaces during drying-wetting/thermal cycles

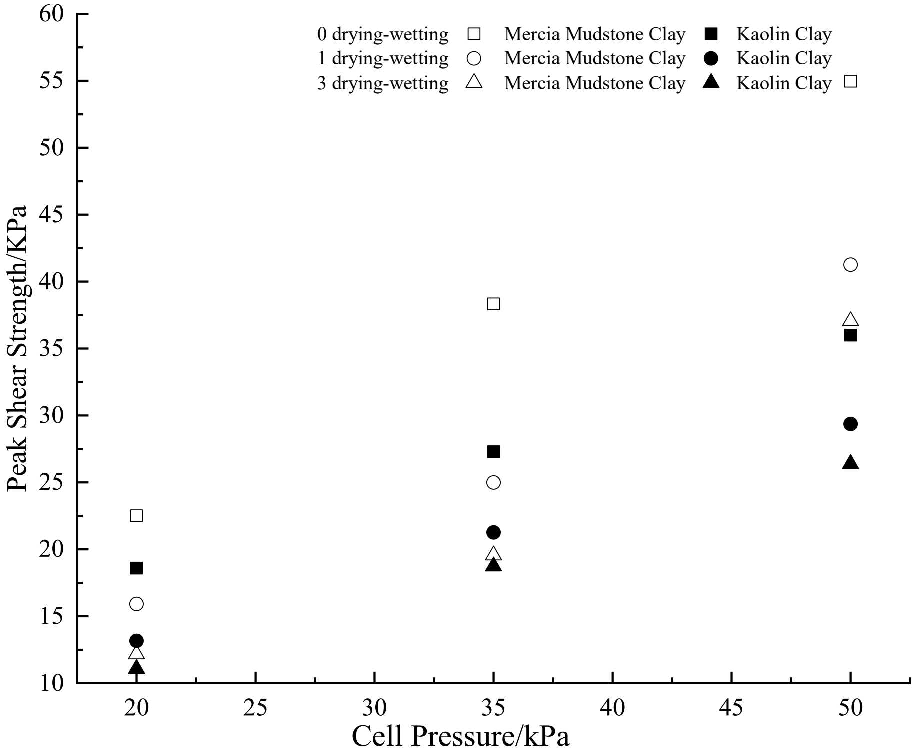


Figure 13 The peak shear strength of soil specimens

Table 1 The basic properties of soil specimens

Properties			Kaolin Clay	Mercia Mudstone Clay
Liquid limit (%)			47	33.63
Plastic limit (%)			26.58	17.42
Plasticity index (%)			20.42	16.23
Maximum dry density (g/cm^3)			2.0	1.93
Optimum water content (%)			20	11.76
Saturated water content (%)			56.36	68.43
Triaxially consolidated undrained shear	Cell Pressure (kPa)	20	18.59	24.12
		35	27.29	39.72
		50	35.99	55.32

strength (kPa)				
Percentage passing (%)	Sieve size (mm)	5.6	100	100
		4	100	99.68
		2	100	84.79
		1	100	52.36
		0.1	100	6.26
		0.05	92	2.39

Table.2 The properties of Geocomposite Drainage Layer

GDL properties	GDL
Thickness of drainage core at 2kPa (mm)	6
Drainage core type	Single direction cuspate core
Mass per unit area (g/m²)	840
Tensile strength of machine direction (kN/m)	22
Elongation at peak of machine direction (%)	45
CBR puncture resistance (N)	3750

Geotextile properties	Bonded on the dimple side	Bonded on the flat side
Thickness at 2kPa (mm)	1.75	1.2
Tensile strength of machine direction (kN/m)	20	9.5
Pore size 090 (µm)	70	120
CBR puncture resistance (N)	3400	1600
Dynamic perforation cone drop (mm)	17	32