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Effect of drying–wetting cycles on the hydromechanical behaviour of compacted coal gangue

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Compacted coal gangue is often used as subgrade soils in South Central China. To understand further the effects of drying–wetting (D-W) cycles on the hydromechanical behaviour of compacted coal gangue subgrade, this paper presents a series of laboratory test results on reconstituted coal gangue subjected to multiple D-W cycles. The effects of vertical load and compaction parameters on the soil deformation behaviours during hydraulic loading are fully discussed. Based on the laboratory investigations, the shrinkage strain was found to decrease with the increase in the initial dry density; however, it increased with the increase in vertical load. Experimental results also revealed that the variation in soil water content was more pronounced in the first D-W cycle. The characteristics of the void ratio and water content change during D-W cycles were investigated, and the shrinkage behaviour (*e*–*w*) was obtained. Significant hysteresis was detected during the D-W cycles, and the size of the hysteresis loop was found to decrease with the increase in D-W cycles, while it increased with the increase in vertical load. Besides, the D-W cycles were found to influence the pore volume at the microscopic scale, where both the volumes of inter-aggregate pores and intra-aggregate pores were found to decrease as the hydraulic loading increased.

Notation

C_c	coefficient of curvature
C_u	coefficient of uniformity
$D_{compaction}$	compaction degree
e	void ratio
G_s	specific gravity
S_r	degree of saturation
w	water content
ρ_d	dry density
ρ_{dmax}	maximum dry density
σ_n	vertical stress

Introduction

In South Central China, compacted coarse soils such as coal gangue are widely used as subgrade materials according to the Chinese standard TB 10621-2014 (NRA, 2014). In the field, subgrade soils are usually unsaturated and subjected to seasonal drying–wetting (D-W) cycles, which may significantly alter the soil moisture distribution and hydromechanical behaviours (Chen and Ng, 2013). In the past decades, numerous studies have been conducted on the role of water transfer in the hydraulic behaviour of unsaturated soil. The results show that the soil fabric, void ratio and water flow are significantly affected by the periodical D-W cycles (Alonso *et al*., 2005; Cuisinier and Masrouri, 2005; Duong *et al*., 2016; Li *et al*., 2017; Rao and Revanasiddappa, 2006; Tang *et al*., 2016). These effects lead to the formation of cracks, as well as the development of fissures in soils. The presence of cracks has a great impact on the long-term serviceability of the pavement, which is one of the important factors that are of concern to owners and designers (Albrecht and Benson, 2001; Simms and Yanful, 2001). Therefore, it is essential to understand the effects of multiple D-W cycles on the soil hydromechanical properties.

Consolidation is a common method of improving the mechanical properties of soils in earthworks such as embankment, highways and railways. According to the Chinese standard TB 10621-2014 (NRA, 2014), the compaction degree of the subgrade soil should be greater than 0.95 to guarantee the performance of the trackbed or pavement. However, due to the difference in construction standards in different countries, it is inevitable to keep the compaction degree at a certain value. From a practical point of view, it is important to investigate the effect of the compaction degree on the hydromechanical properties of this kind of subgrade soil. The effect of the compaction degree on the soil water retention behaviour has been reported by many researchers (Chen *et al*., 2019; Gallage and Uchimura, 2010; Hu *et al*., 2013; Li *et al*., 2009; Salager *et al*., 2010; Wijaya and Leong, 2017; Zhou *et al*., 2012). They reported that there is a great influence on the soil water retention curve at a low suction range. However, the effect of the compaction degree on the hydromechanical behaviour of coal gangue subgrade soil is not commonly found in the literature.

The soil hydromechanical behaviour is strongly affected by the microstructure. In the literature, the soil microstructure has been studied extensively from qualitative and quantitative levels by using scanning electron microscopy (SEM), mercury intrusion porosimetry (MIP), computed tomography and atomic force microscopy methods (Beckett and Augarde, 2013; Ravi *et al*., 2006; Romero and Simms, 2008; Sun and Cui, 2017). Generally, multiple D-W cycles are usually accompanied by rearrangement of soil particles, which results in changes in the pore system and soil aggregation (Cai *et al*., 2019; Kong *et al*., 2018; Pires *et al*., 2008; Sun and Cui, 2017). A comprehensive understanding of the soil microstructure response to hydraulic loading is essential for the anticipation of soil physical behaviour.

The coal gangue is a common solid waste produced from the coal industry. It is usually used as aggregate in infrastructure construction due to its low pozzolanic activity (Cong *et al*., 2016; Hongqiang *et al*., 2019). Due to the diversity of coal during geological evolution, the mineral content of coal gangue in different coal industries is relatively complex and therefore results in huge differences in its physical properties (Li *et al*., 2006). Under the coupling effect of hydraulic and mechanical loading, the coarse particles of coal gangue are prone to disintegration, which will in turn cause cracks, collapses and uneven settlement of the existing pavement structure. Therefore, the study of the hydromechanical behaviour of coal gangue is of great importance on the service performance of infrastructures that are built with coal gangue materials.

The aforementioned studies provided a rich database for analysing the volume change behaviour of soils on D-W cycles. Most of the research on soil hydromechanical behaviour is mainly focused on fine-grained soils (Delage and Lefebvre, 1984; Monroy *et al*., 2010; Yang *et al*., 2019); the relevant studies involving coal gangue are limited. Moreover, the variations in the void ratio and water content during cyclic D-W are the most critical factors that affect the long-term performance of subgrades. The aforementioned studies are limited to change in void ratio under a certain suction value. The change process of the void ratio and water content with time have rarely been published. This research was focused on the effects of D-W cycles on the hydromechanical behaviour of coal gangue. Laboratory tests were conducted on compacted coal gangue soils with different compaction degrees and vertical loads. Particular attention was paid to the evolution of the void ratio and water content change during multiple D-W cycles. Moreover, MIP and SEM techniques were employed for further understanding of the effects of D-W cycles on the microstructure of coal gangue at different compaction degrees.

Materials and sample preparation

The test soil investigated in this study is a coal gangue recovered from the Yi-Lou Expressway Section in Central South China. High-quality intact block samples were manually extracted and were immediately wrapped in a thick plastic membrane. Figure 1 shows the grain size distribution curves of the tested coal gangue. The coefficient of curvature, C_c, and coefficient of uniformity, C_u,

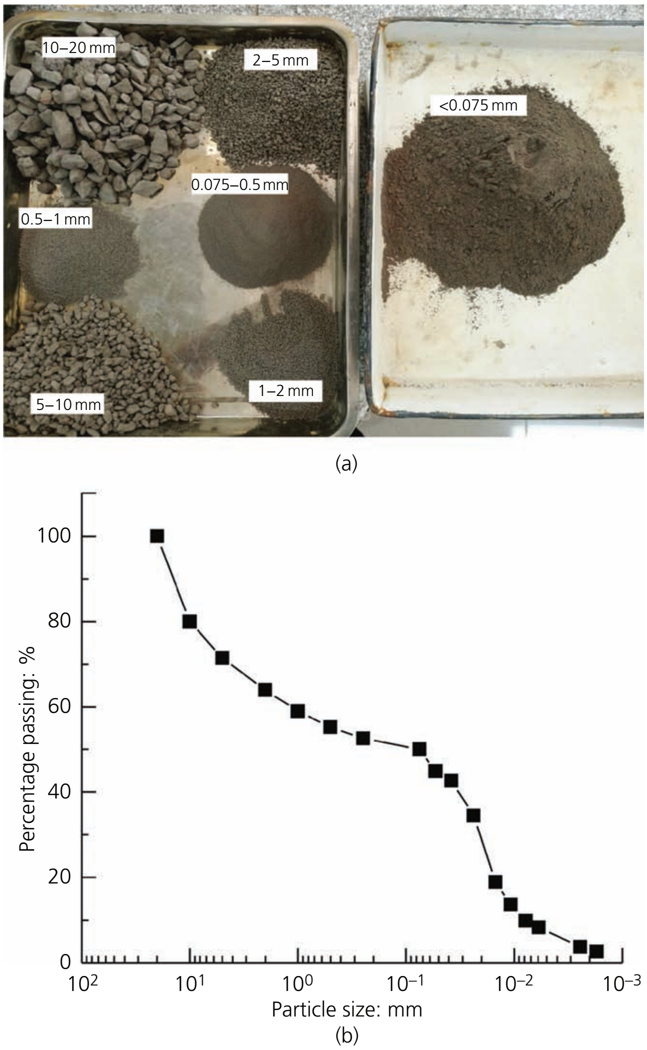

Figure 1. (a) Photographs of coal gangue; (b) grain size distribution curve of coal gangue

are 0.048 and 147.42, respectively. According to the Unified Soil Classification System, the tested soils are classified as silty sand (ASTM, 2017). The X-ray diffraction analysis showed that the main minerals in the coal gangue were 39.78% quartz, 26.37% calcite, 11.32% pyrite, 9.26% chlorite, 8.47% montmorillonite and 4% mica. Other index properties are summarised in Table 1.

Oedometer specimens with a 100 mm diameter and a 40 mm height were prepared for the consolidation test. The maximum grain size was controlled to be 20 mm to eliminate the sample size effect on the mechanical behaviour of soil. The soil was compacted in three layers with scarification between layers to guarantee homogeneity. Two groups of the compaction degree (0.85 and 0.90) were set to study the effect of the compaction degree on the soil mechanical behaviour. Note that the different compaction degrees were achieved by controlling the dry density ($D_{compaction} = \rho_d/\rho_{dmax}$, with $D_{compaction}$, ρ_d and ρ_{dmax} being the

Table 1. Index properties of coal gangue

Property	Value
Specific gravity	2.74
Standard compaction tests	
Maximum dry unit weight: g/cm^3	2.31
Optimum water content: %	8.2
Atterberg limits of fines	
Liquid limit: %	31.81
Plastic limit: %	18.10
Plasticity index: %	13.71

compaction degree, dry density and maximum dry density, respectively). Figure 2 shows the soil-water characteristic curve (SWCC) results of test specimens with different compaction degrees (Chen *et al.*, 2020). The drainage curve of the coal gangue exhibits a bimodal SWCC. With the increase in the compaction degree, the bimodal characteristics weaken. The volumetric water content of the coal gangue reduces rapidly in a low suction range (0.01–5 kPa). When the suction is greater than 100 kPa, the drainage curves of coal gangue under different compactions tend to overlap with each other.

Test programme and procedure

Compression tests

The test programme consists of six stress-controlled D-W tests. Detailed test plans are summarised in Table 2. Each test was conducted with two identical samples prepared using the same procedure and tested in parallel, one for measurement of the change in void ratio and the other for the variation in water content during the D-W process. After preparation of the specimens, the soil samples were first saturated with distilled water using a vacuum pump. Later the specimen was placed in

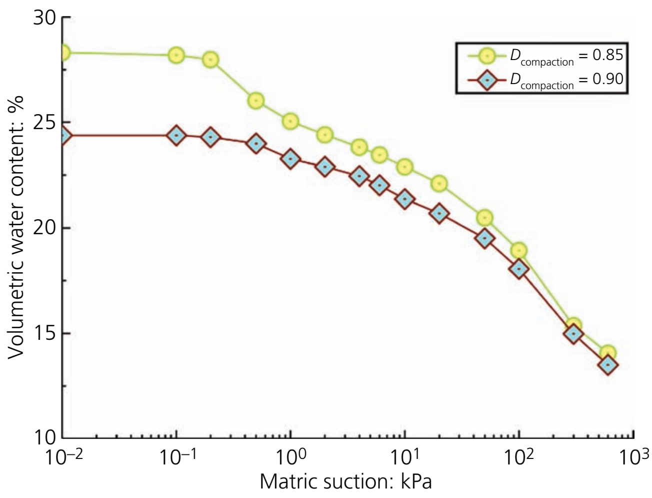

Figure 2. SWCC of coal gangue with different compaction degrees (Chen *et al.*, 2020)

Table 2. Summary of test programmes and conditions

Compaction degree	Vertical load: kPa	Number of D-W cycles	Series
0.85	5	4	Compression tests
0.85	100	4	
0.85	200	4	
0.90	5	4	
0.90	100	4	
0.90	200	4	
0.90	200	— (parallel test)	
0.90	200	0	Microstructural tests
0.90	200	1	
0.90	200	4	

the oedometer, and a net vertical stress (i.e. 5, 100 or 200 kPa) was applied to the soil specimen under saturated conditions (Figure 3). The end of primary consolidation was determined by following method B of ASTM D 2435 (ASTM, 2011) (i.e. once 90% consolidation was achieved, subsequent load increments were applied). The dehydration process was started after the deformation had reached equilibrium. The sample was dehydrated by air-drying. During the drainage process, the water in the consolidometer was removed and a small fan was utilised to accelerate the drainage. The axial deformation was recorded at time intervals of 1, 2, 4, 8, 12, 24, 36, 48, 60, 72, 84, 100, 120, 132 and 144 h (6 days). Then, the sample was re-saturated by adding the water again in the consolidometer. The axial deformation was recorded at time intervals of 4 min, 8 min, 15 min, 30 min, 1 h, 2 h, 4 h, 8 h, 12 h and 24 h. This was considered one D-W cycle, and the process was repeated until the desired numbers of D-W cycles (first, second, third, fourth) were completed. Besides, a parallel test was also conducted to investigate the magnitude of multiple D-W cycles on the soil volumetric deformation. Specimens with an initial compaction degree of 0.90 were selected, and the net vertical stress was set as 200 kPa. No dehydration/imbibition process was applied to the sample. The deformation was recorded at the same time interval as described earlier during the entire four cycles. For the series of water content measurements, the gravimetric water content was detected by weighing the oedometer ring and specimen immediately with a digital scale. Thereafter, the oedometer ring and specimen were placed inside the oedometer again. The dehydration/imbibition process was continued after the deformation of sample had reached a value before unloading.

Microstructural tests

MIP tests and SEM tests were conducted on the coal gangue at a compaction degree of 0.90 under a net vertical stress of 200 kPa with different D-W cycles. Detailed test plans are summarised in Table 2. The soil samples were initially dehydrated and wetted by using the same procedure as mentioned earlier. After the desired numbers of D-W cycles had been reached, the samples were carefully broken down into small pieces. A freeze-drying technique conducted by means of liquid nitrogen and isopentane

(a) (b) (c)

Figure 3. (a) Specimen preparation; (b) testing; (c) specimen after multiple D-W cycles

was utilised to dehydrate the soil pieces. Subsequently, the pieces were divided into two parts, one for MIP tests and another for SEM tests. In the SEM tests, the samples were coated with gold powder to perform visualisation of the soil surface fabric, which was conducted by using a JSM-6490LV φ Neptune Tex s HP scanning electron microscope. As for MIP tests, the samples were first put in a dilatometer and then injected with mercury by using an AutoPore IV 9500 mercury intrusion porosimeter. The intruded pressure was increased slowly from low pressure (1.52 kPa (0.22 pounds per square inch absolute (psia))) to high pressure (206.8 MPa (30 000 psia)), and the mercury volume was measured after each pressure increment. Based on the assumption of the bundled cylindrical capillary approach, the pore diameter can be calculated with the surface tension of mercury (0.485 N/m) and intruded pressure by using the Young–Laplace equation. The corresponding pore diameter measurement range was 6.0 nm–813 μm.

Experimental results and discussion

Variation in void ratio during D-W cycles

Figure 4 shows the shrinkage and swelling curves measured along the drying and wetting paths. It should be noted that all the stresses in the legend of the figure in this paper are vertical stress. The change in void ratio during initial loading is not presented in this figure. As expected, the soil sample exhibited a decrease in void ratio on the drying path and an increase in void ratio on the wetting path. As the applied vertical stress increased, the wetting-induced swelling is attenuated. To understand further the effect of multiple D-W cycles on the hydromechanical behaviour of recompacted coal gangue, the variation in void ratio is replotted by axial strain in Figure 5. It can be seen that the compression behaviour of recompacted coal gangue is highly affected by hydraulic cycles. For the specimen prepared at a compaction degree of 0.90 under a net vertical stress of 200 kPa, the accumulative axial strains for one, two and four cycles are 5.72, 6.82 and 8.00%, respectively. For the same specimen that did not undergo cyclic D-W, the maximum plastic accumulated strain is only 0.11%, which is negligible compared with that of the specimen subjected to D-W cycles (Figure 5(b)).

It is noticed that the irreversible soil shrinkage induced by cyclic D-W is more significant in the first cycle than that in the subsequent

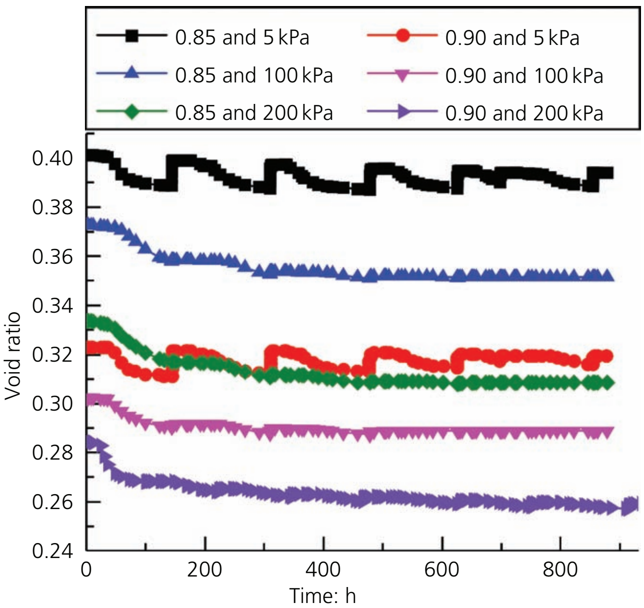

Figure 4. Variations in the void ratio with time during D-W cycles

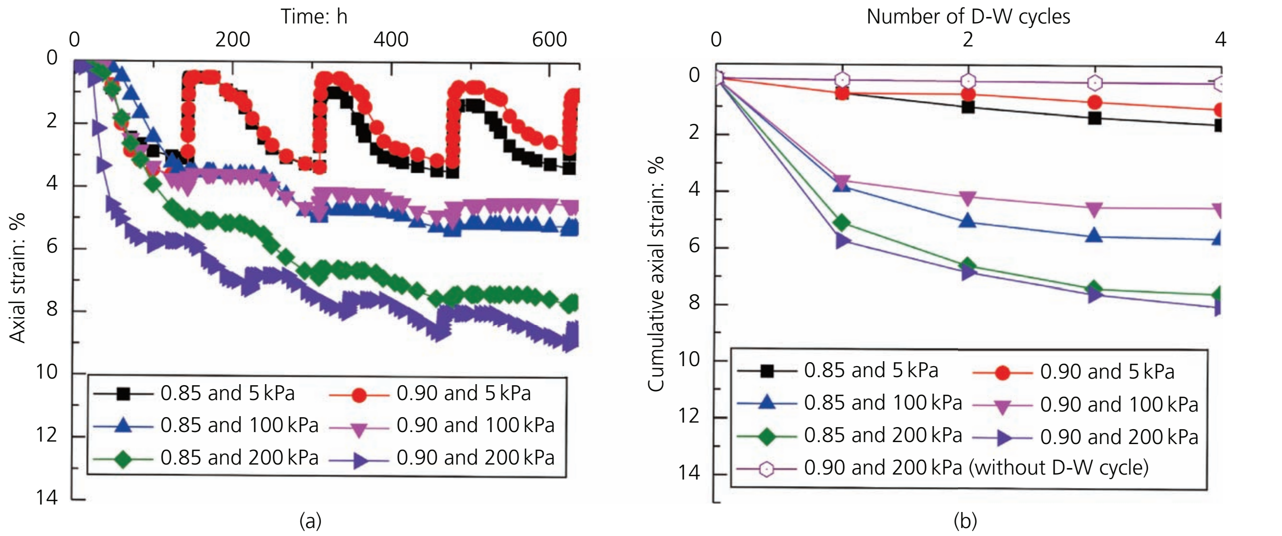

Figure 5. D-W curves of compacted coal gangue: (a) axial strain plotted against time; (b) cumulative axial strain plotted against different D-W cycles

cycles. Also, for the example of the sample with a compaction degree of 0.90 and under a net vertical stress of 200 kPa, the increments in the soil accumulative strain from cycle 0 → 1 and 1 → 4 are 5.72 and 2.28%, respectively. A similar experimental result was also reported in the literature (Nowamooz and Masrouri, 2010). The significant increase in axial strain at the first cycle can be explained by the suction-increase (SI) curve in the Barcelona basic model. Under the first drying cycle, the specimen will touch the inherent SI curve, generate elastoplastic deformation and put the SI curve to a new station. However, due to the hydraulic hysteresis, there will be a suction difference between the soils undergoing different D-W cycles. In other words, the suction values at the end of the drying path in the subsequent cycle are lower than that in the first cycle. Therefore, the specimen at the subsequent cycle will not touch the SI curve and the resulting axial stain will also be reduced. Moreover, it seems that the subsequent D-W cycles also play an important role in soil mechanical behaviour. Many studies have shown that the mechanical and hydraulic behaviours of unsaturated soils are fully coupled (Burton *et al*., 2014; Zhang *et al*., 2016). In the presented constitutive model, such as the Barcelona model (Alonso *et al*., 1990) or Sheng–Fredlund–Gens model (Sheng *et al*., 2008), they were concerned only with the irreversible soil deformation at the first D-W cycle. For the coal gangue, large plastic cumulative strain still exists in the subsequent D-W cycle. Particularly at relatively low vertical stress (σ_n = 5 kPa), the increments in accumulative strain from cycle 1 → 4 for soil with compaction degrees of 0.85 and 0.90 are 1.06 and 0.52%, respectively, which are 2.07 and 1.02 times of the cumulative strain increment from cycle 0 → 1 (Figure 5(b)).

In comparisons of variations in the axial strain with the compaction degree at different D-W cycles, it is noted that the impact of the compaction degree is insignificant at the first two D-W cycles. The drying-induced soil shrinkage is almost the same with different compaction degrees at a relatively low vertical stress ($\sigma_n \leq 100$ kPa). It can be seen that the irreversible volumetric deformation during the first two D-W cycles is mainly controlled by the wetting-induced swelling. Under a 'denser' state, the swelling will be more significant. Under a relatively high vertical stress, the effect of the compaction degree is predominant on the beginning of the dehydration process. Even though the soil sample experienced four D-W cycles, it seems that irreversible volumetric deformation of the sample with a compaction degree of 0.90 still has not reached a steady state. The effect of wetting–drying (W-D) on the soil deformation of compacted swelling clays was investigated by Cui *et al*. (2002). The results revealed that the irreversible volumetric deformation during W-D cycles is a function of compaction conditions and the subsequent variation in stress/hydration paths. In this investigation, the results reveal that the irreversible volumetric strain is mainly affected by the vertical stress in the first two D-W cycles. As the D-W cycles increased, the influence of the compaction degree kicked in.

Variation in water content during D-W cycles

The variations in the water content of coal gangue with different initial conditions are shown in Figure 6. It can be observed that the saturated water content of coal gangue at a vertical stress of 5 kPa is much higher than that at 100 kPa during the entire D-W cycles. Moreover, the difference in saturated water content between 100 and 200 kPa is insignificant after each D-W cycle. It should be noted that the samples are not saturated after a day of water immersion. Hereafter, the 'saturated water content' only represents the water content after each wetting process.

The normalised water content of coal gangue with different initial conditions is presented in Figure 7. The saturated water content *w*

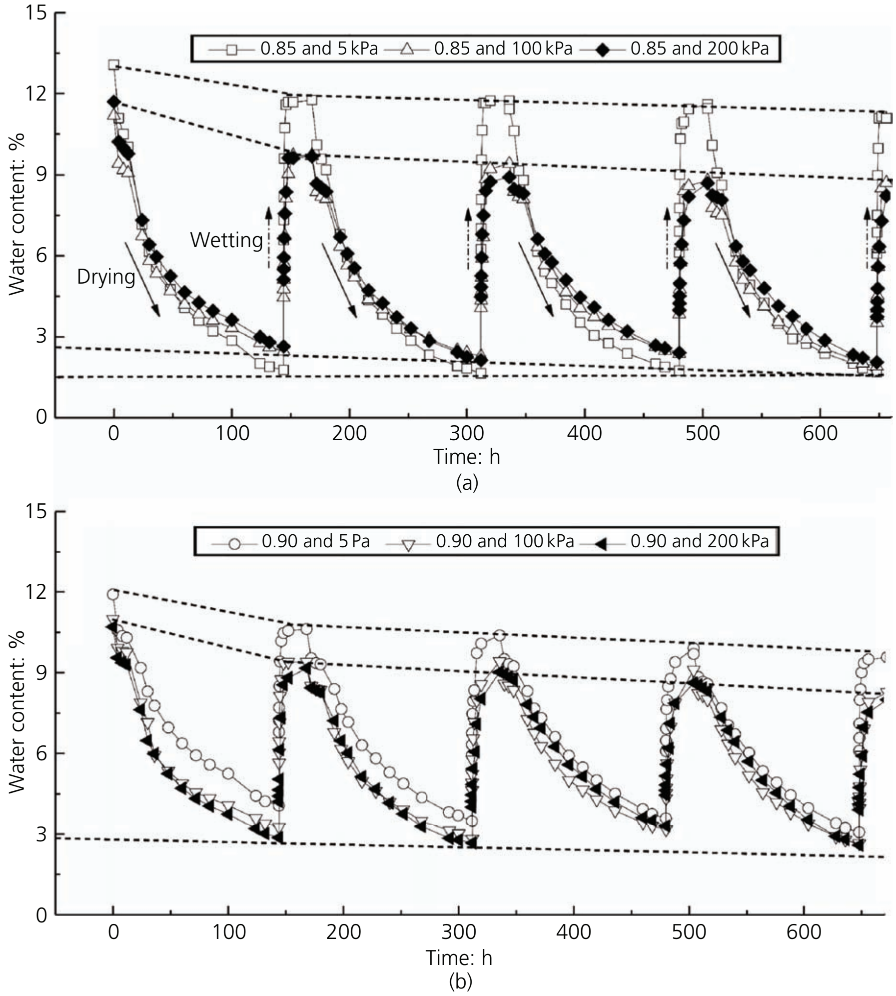

Figure 6. Variations in the water content with time during D-W cycles: (a) $D_{compaction}$ = 0.85; (b) $D_{compaction}$ = 0.90

after each D-W cycle is divided by the initial water content to evaluate the soil water retention ability at each D-W cycle. When the variation in void ratio is plotted, the change in the water content is very pronounced in the first cycle but decreases at the subsequent cycles. As the applied vertical stress increases, a more drastic decrease in saturated water content is detected at each D-W cycle. Quantitatively, as the imposed vertical stress increases from 5 kPa to 200 kPa after the first D-W cycle, the normalised water content w/w_0 of coal gangue at a compaction degree of 0.85 decreases from 0.89 to 0.85. The water content during each D-W cycle can be checked by using the value of eS_r/G_s, where G_s is the specific gravity of the soil. It can be seen that the water content is positively related to the void ratio. According to the result of accumulated axial strain presented in Figure 5(b), a relatively high vertical stress is observed and generally produces a larger soil deformation after cyclic D-W, which is considered to be the primary reason leading to the variation in water content for different vertical stresses. However, the water content is also affected by the degree of saturation. It is confirmed that there is a tiny difference in S_r after a day of immersion and the effect of S_r can be ignored at the saturated stage.

Variation in void ratio against water content during D-W cycles

Variations in the void ratio against the water content of coal gangue with a compaction degree of 0.85 at different D-W cycles are shown in Figure 8. Two typical shrinkage stages were seen during the dehydration process, and the slope of the second shrinkage stage decreases with the increase in D-W cycles. In the first shrinkage stage, the volume shrinkage of the soil is much smaller than the volume of water evaporation. With further drying, the slope of the shrinkage curve increases significantly when the water content reaches a specific water content w^*. This marks the second shrinkage stage, at which the major deformation of the soil sample is completed. This phenomenon might relate to the dual-pore structure (pores inside and between the aggregates at microscale) in the soil sample (Chen *et al*., 2019; Li and Zhang, 2009; Rahardjo *et al*., 2004; Romero *et al*., 1999). During

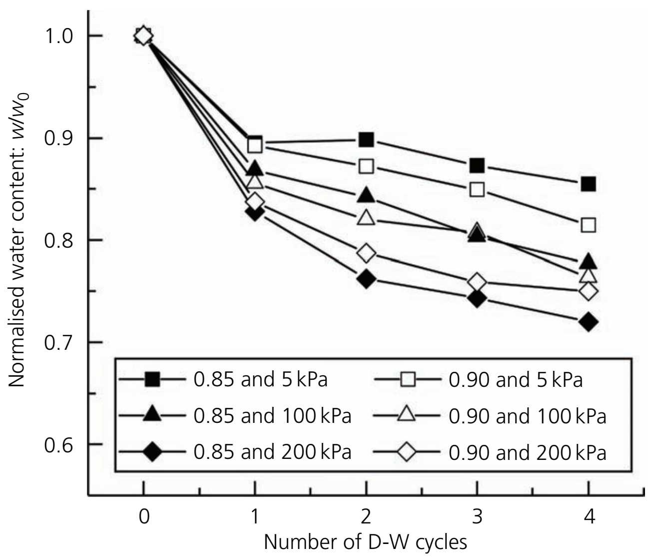

Figure 7. Influence of D-W cycles on the normalised water content

the drainage process, the water stored in the macropore structure first evaporates and is gradually replaced by air, and no capillary water pressure is generated. Therefore, only a tiny soil deformation is observed in the first shrinkage stage. When the water content is lower than the specific water content w^*, the dehydration of water stored in the microstructure kicks in. Previous research on compacted clay-based soils has clarified that hydraulic loading will alter the volume of micropores (Li *et al.*, 2017; Seiphoori *et al.*, 2014). The resulting behaviour is an outcome of a continuous rearrangement of soil particles, which leads to a decrease in void ratio. By considering this type of volumetric behaviour as a benchmark, the shrinkage of the soil sample during D-W can be explained.

According to the traditional soil-shrinkage curve, when the soil approaches the dry state, it is on the zero-shrinkage state. However, in this paper, it can be seen there is still a relatively large shrinkage in this state. This phenomenon may be attributed to the soil sorptive potential (Lu and Zhang, 2019; Zhang and Lu,

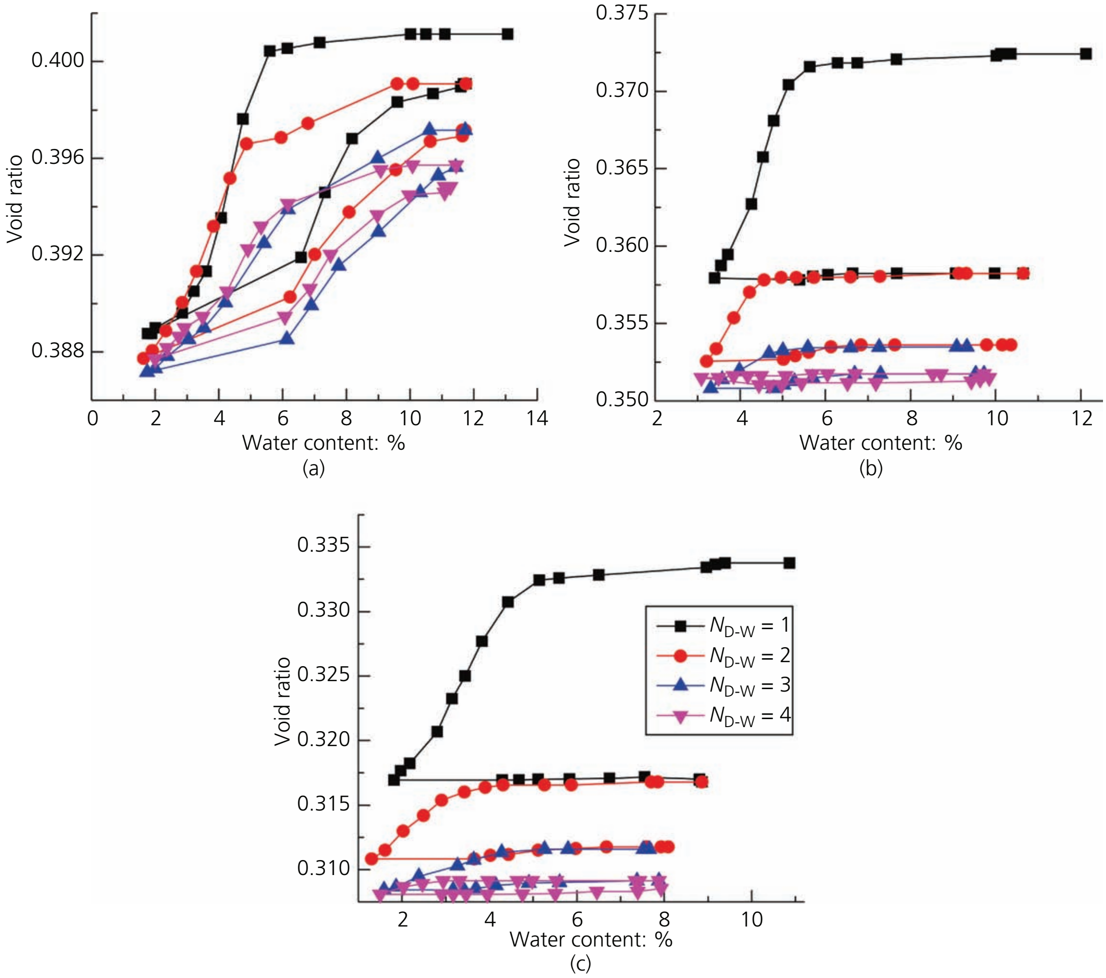

Figure 8. Shrinkage behaviour of coal gangue at a compaction degree of 0.85 under different D-W cycles: (a) σ_n = 5 kPa; (b) σ_n = 100 kPa; (c) σ_n = 200 kPa

2020). The soil sorptive potential is the sum of the locally varying electromagnetic potentials comprising van der Waals attraction, electrical double-layer repulsion and surface and cation hydration (Lu and Zhang, 2019). Lu and Dong (2017) suggested that the soil-shrinkage curve can be divided into four states: capillary, pendular, adsorbed and tightly adsorbed. Drying in the tightly absorbed state causes an onset of dehydration of exchangeable cations in soils and strengthens the van der Waals attraction. Furthermore, due to the 8.47% montmorillonite in coal gangue, the specimen used in this study had a strong cation-exchange capacity. A reduction in water content will result in a high soil sorptive potential and create continuous shrinkage.

Furthermore, marked hysteresis between the D-W cycles of the shrinkage curve is observed in Figure 8. At a given vertical pressure, the size of the hysteresis loop decreased consistently as the number of D-W cycles increased. After the specimen has experienced four D-W cycles, no obvious hysteresis loop was detected at a vertical pressure of 200 kPa. This was likely due to the presence of smaller aggregate pores induced by D-W cycles (see Figure 9). The 'ink-bottle' effect is less significant at a higher number of D-W cycles (Ng *et al*., 2016). Moreover, a smaller difference in contact angle existed between the dehydration and imbibition processes, which indicated a decrease in water retention capacity with increasing D-W cycles. As a result, the slope of the shrinkage curve at the second shrinkage decreased after cyclic hydraulic loading, and the hysteresis loop became smaller. From Figures 8(a) and 8(b), it can be found that the e–w curves are somewhat stress dependent. The size of the hysteresis loop appears to be larger under higher vertical stress. The effect of vertical stress on the hysteresis loop is primarily controlled by swelling. The magnitude and rate of volumetric swelling on wetting decreased with an increase in the applied vertical stress. Similar observations were reported by Alonso *et al*. (2005). From the microscopic viewpoint, the efficiency of translating interlayer swelling to bulk volume increase is reduced with an increase in vertical stress, which is similar to the previous observations that a larger confining stress results in a more stable soil texture.

Variation in the microstructure during D-W cycles

The pore-size distributions from MIP measurement of the samples under different D-W cycles are shown in Figure 9. The cumulative pore volumes of coal gangue are found to decrease with increased D-W cycles (see Figure 9(a)). Accordingly, a significant decrease in the maximum mercury intruded volume was observed in the first D-W cycle, which was consistent with the result of the void ratio measurement. The maximum mercury intruded volume change in zero, one and four cycles are 0.092, 0.085 and 0.051 ml/g, respectively. The pore-size distribution functions of coal gangue varying from different D-W cycles are presented in Figure 9(b). The pore-size distribution curve of coal gangue shows an evident bimodal peak, which is clearly characterised by two peaks corresponding to diameters of 0.3 μm (primary peak) and 40 μm (secondary peak). When the number of D-W cycles increased, both the volumes of inter-aggregate pores and intra-aggregate pores were reduced, while the diameter was found to be independent with hydraulic loading. Similar experimental observations were also reported by Li *et al*. (2017). In the study of Li *et al*. (2017), however, only the volume of inter-aggregate pores was found to be affected by the cyclic D-W. The decrement in the volume of intra-aggregate pores may be due to the disintegration of coal gangue during cyclic D-W. Tang *et al*. (2016) found that a series of D-W cycles will result in breakdown of aggregates, which will lead to an increase of the fines. In the oedometer test, the volume change of the micropores leads to either accumulated shrinkage or accumulated swelling in the macropores (Al-Dakheeli and Bulut, 2019).

SEM micrographs of coal gangue with different D-W cycles are presented in Figure 10. With ×5000 magnification, the variation in

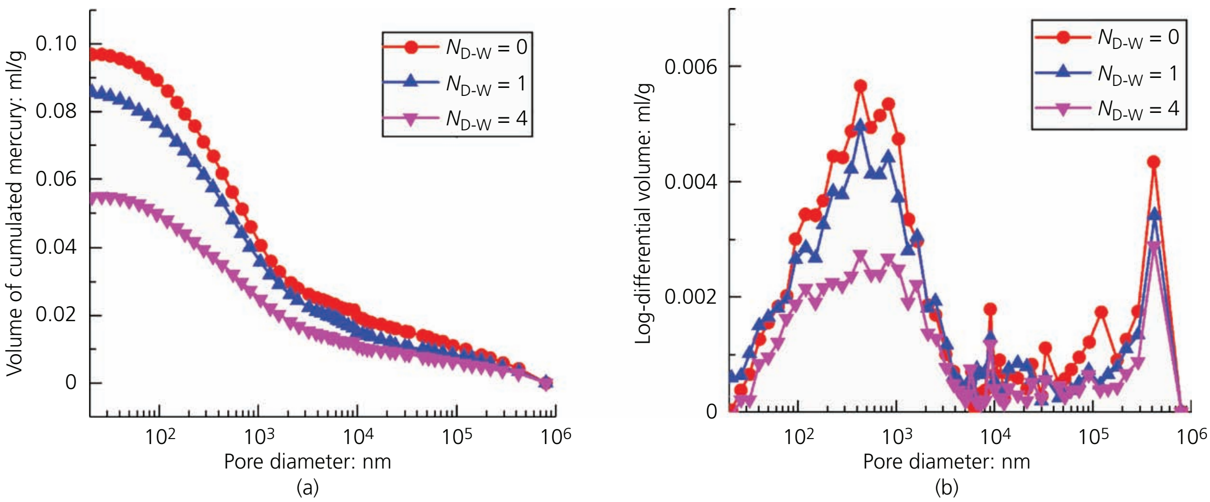

Figure 9. MIP results of coal gangue under different D-W cycles: (a) cumulative intrusion void ratio; (b) pore-size density function

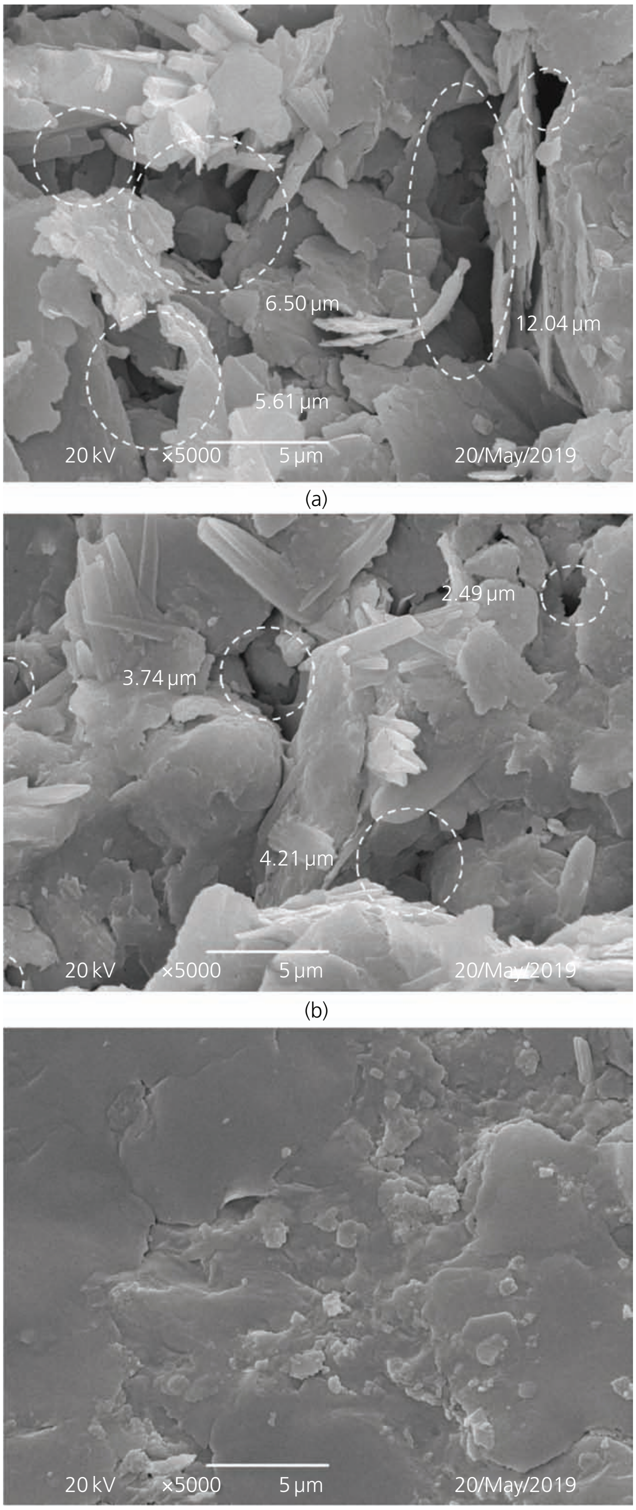

Figure 10. SEM results of coal gangue under different D-W cycles: (a) $N_{\text{D-W}} = 0$; (b) $N_{\text{D-W}} = 1$; (c) $N_{\text{D-W}} = 4$

intra-aggregate pores becomes more eye-catching. It was observed that the volume of the intra-aggregate pores decreased significantly with increased D-W cycles. After four cycles of D-W, the open inter-aggregate pores in the soil fabric became almost closed. The results observed in SEM images were in accordance with MIP results. It can be seen that the applied D-W cycles were accompanied by a continual rearrangement of the soil structure.

Conclusions

The microstructure and hydromechanical behaviours of compacted coal gangue under different loadings and multiple D-W cycles were investigated in this research. Based on the laboratory investigations, the major conclusions are listed as follows.

- The shrinkage behaviour is significantly influenced by the initial dry density and vertical load. It is observed that shrinkage strain decreases with the increase in the initial dry density, while it increases with the increase in vertical load.
- The change in void ratio and water content induced by cyclic D-W is more significant in the first cycle than in the subsequent cycles and will reach an asymptotic value as the cycle number increases.
- Two typical shrinkage stages are observed during the dehydration process; the slope of the second shrinkage stage decreases with the increase in D-W cycles.
- It is evident that deformation behaviour of coal gangue is affected by cyclic D-W. In the zero-shrinkage state, there is still a relatively large shrinkage for this kind of soil. For those empirically based design guides considering the effects of soil moisture on soil behaviour and properties, the measured results from cyclic D-W tests should be adopted for calibrating these empirical models.
- The *e*–*w* curves are found to be stress dependent. There is a significant hysteresis of axial strain between the D-W curves. The size of the hysteresis loop was found to decrease with the increase in D-W cycles, while it increased with the increase in vertical load.
- The pore-size distribution curve of coal gangue showed an evident bimodal feature. Both the inter-aggregate pores and intra-aggregate pores were affected by hydraulic loading. However, hydraulic loading influenced only the pore volume, whereas the diameter of pores was found independent with suction cycles.

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REFERENCES

Albrecht BA and Benson CH (2001) Effect of desiccation on compacted natural clays. *Journal of Geotechnical and Geoenvironmental Engineering* **128(4)**: 67–75, http://doi.org/10.1061/(ASCE)1090-0241(2001)127:1(67).

Al-Dakheeli H and Bulut R (2019) Interrelationship between elastic deformation and soil-water characteristic curve of expansive soils. *Journal of Geotechnical and Geoenvironmental Engineering* **145(4)**: article 04019005, http://doi.org/10.1061/(asce)gt.1943-5606.0002020.

Alonso EE, Gens A and Josa A (1990) A constitutive model for partially saturated soils. *Géotechnique* **40(3)**: 405–430, http://doi.org/10.1680/geot.1990.40.3.405.

Alonso EE, Romero E, Hoffmann C and García-Escudero E (2005) Expansive bentonite–sand mixtures in cyclic controlled-suction drying and wetting. *Engineering Geology* **81(3)**: 213–226, http://doi.org/10.1016/j.enggeo.2005.06.009.

ASTM (2011) D 2435/D 2435M-11: Standard test methods for one-dimensional consolidation properties of soils using incremental loading. ASTM International, West Conshohocken, PA, USA.

ASTM (2017) D 2487-17: Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). ASTM International, West Conshohocken, PA, USA.

Beckett CTS and Augarde CE (2013) Prediction of soil water retention properties using pore-size distribution and porosity. *Canadian Geotechnical Journal* **50(4)**: 435–450, http://doi.org/10.1139/cgj-2012-0320.

Burton GJ, Sheng D and Airey D (2014) Experimental study on volumetric behaviour of Maryland clay and the role of degree of saturation. *Canadian Geotechnical Journal* **51(12)**: 1449–1455, https://doi.org/10.1139/cgj-2013-0332.

Cai GH, Liu SY and Zheng X (2019) Influence of drying–wetting cycles on engineering properties of carbonated silt admixed with reactive MgO. *Construction and Building Materials* **204(20)**: 84–93, http://doi.org/10.1016/j.conbuildmat.2019.01.125.

Chen R and Ng CWW (2013) Impact of wetting–drying cycles on hydro-mechanical behavior of an unsaturated compacted clay. *Applied Clay Science* **86(2013)**: 38–46, http://doi.org/10.1016/j.clay.2013.09.018.

Chen RP, Liu P, Liu XM, Wang PF and Kang X (2019) Pore-scale model for estimating the bimodal soil–water characteristic curve and hydraulic conductivity of compacted soils with different initial densities. *Engineering Geology* **260(3)**: article 105199, http://doi.org/10.1016/j.enggeo.2019.105199.

Chen RP, Wang PF, Liu P *et al.* (2020) Experimental study on soil-water characteristic curves of subgrade coal gangue filler. *Rock and Soil Mechanics* **41(02)**: 372–378, http://doi.org/10.16285/j.rsm.2019.0372.

Cong XY, Lu S, Yao Y and Wang Z (2016) Fabrication and characterization of self-ignition coal gangue autoclaved aerated concrete. *Materials & Design* **97(5)**: 155–162, http://doi.org/10.1016/j.matdes.2016.02.068.

Cui YJ, Yahia-Aissa M and Delage P (2002) A model for the volume change behavior of heavily compacted swelling clays. *Engineering Geology* **64(2)**: 233–250, http://doi.org/10.1016/S0013-7952(01)00113-2.

Cuisinier O and Masrouri F (2005) Hydromechanical behaviour of a compacted swelling soil over a wide suction range. *Engineering Geology* **81(3)**: 204–212, https://doi.org/10.1016/j.enggeo.2005.06.008.

Delage P and Lefebvre G (1984) Study of the structure of a sensitive Champlain clay and of its evolution during consolidation. *Canadian Geotechnical Journal* **21(1)**: 21–35, http://doi.org/10.1139/t84-003.

Duong TV, Cui YJ, Tang AM *et al.* (2016) Effects of water and fines contents on the resilient modulus of the interlayer soil of railway substructure. *Acta Geotechnica* **11(1)**: 51–59, http://doi.org/10.1007/s11440-014-0341-0.

Gallage CPK and Uchimura T (2010) Effects of dry density and grain size distribution on soil-water characteristic curves of sandy soils. *Soils and Foundations* **50(1)**: 161–172, http://doi.org/10.3208/sandf.50.161.

Hongqiang M, Hongyu C, Hongguang Z *et al.* (2019) Study on the drying shrinkage of alkali-activated coal gangue-slag mortar and its mechanisms. *Construction and Building Materials* **225(50)**: 204–213, http://doi.org/10.1016/j.conbuildmat.2019.07.258.

Hu R, Chen YF, Liu HH and Zhou CB (2013) A water retention curve and unsaturated hydraulic conductivity model for deformable soils: consideration of the change in pore-size distribution. *Géotechnique* **63(16)**: 1389–1405, http://doi.org/10.1680/geot.12.P.182.

Kong L, Sayem HM and Tian H (2018) Influence of drying–wetting cycles on soil-water characteristic curve of undisturbed granite residual soils and microstructure mechanism by nuclear magnetic resonance (NMR) spin–spin relaxation time (T2) relaxometry. *Canadian Geotechnical Journal* **55(2)**: 208–216, http://doi.org/10.1139/cgj-2016-0614.

Li X and Zhang LM (2009) Characterization of dual-structure pore-size distribution of soil. *Canadian Geotechnical Journal* **46(46)**: 129–141, http://doi.org/10.1139/T08-110.

Li D, Song X, Gong C and Pan Z (2006) Research on cementitious behavior and mechanism of pozzolanic cement with coal gangue. *Cement and Concrete Research* **36(9)**: 1752–1759, http://doi.org/10.1016/j.cemconres.2004.11.004.

Li X, Zhang LM and Li JH (2009) Development of a modified axis translation technique for measuring SWCCs for gravel soils at very low suctions. *Geotechnical Testing Journal* **32(6)**: article 102201, http://doi.org/10.1520/gtj102201.

Li ZS, Fleureau JM and Tang LS (2017) Aspects of compaction and drying–wetting curves of a subgrade clayey soil. *Géotechnique* **67(12)**: 1120–1126, http://doi.org/10.1680/jgeot.16.T.010.

Lu N and Dong Y (2017) Correlation between soil-shrinkage curve and water-retention characteristics. *Journal of Geotechnical and Geoenvironmental Engineering* **143(9)**: 04017054, http://doi.org/10.1061/(asce)gt.1943-5606.0001741.

Lu N and Zhang C (2019) Soil sorptive potential: concept, theory, and verification. *Journal of Geotechnical and Geoenvironmental Engineering* **145(4)**: article 04019006, http://doi.org/10.1061/(asce)gt.1943-5606.0002025.

Monroy R, Zdravkovic L and Ridley A (2010) Evolution of microstructure in compacted London Clay during wetting and loading. *Géotechnique* **60(2)**: 105–119, http://doi.org/10.1680/geot.8.P.125.

Ng CWW, Sadeghi H, Hossen SKB *et al.* (2016) Water retention and volumetric characteristics of intact and re-compacted loess. *Canadian Geotechnical Journal* **53(8)**: 1258–1269, http://doi.org/10.1139/cgj-2015-0364.

Nowamooz H and Masrouri F (2010) Suction variations and soil fabric of swelling compacted soils. *Journal of Rock Mechanics and Geotechnical Engineering* **2(2)**: 129–134, http://doi.org/10.3724/SP.J.1235.2010.00129.

NRA (National Railway Administration) (2014) TB 10621-2014: Code for design of high speed railway. China Railway Publishing House, Beijing, China.

Pires LF, Cooper M, Cássaro FAM *et al.* (2008) Micromorphological analysis to characterize structure modifications of soil samples submitted to wetting and drying cycles. *Catena* **72(2)**: 297–304, http://doi.org/10.1016/j.catena.2007.06.003.

Rahardjo H, Aung KK, Leong EC and Rezaur RB (2004) Characteristics of residual soils in Singapore as formed by weathering. *Engineering Geology* **73(1)**: 157–169, http://doi.org/10.1016/j.enggeo.2004.01.002.

Rao SM and Revanasiddappa K (2006) Influence of cyclic wetting drying on collapse behaviour of compacted residual soil. *Geotechnical and Geological Engineering* **24(3)**: 725–734, http://doi.org/10.1007/s10706-004-5077-4.

Ravi S, D'Odorico P, Herbert B, Zobeck T and Over TM (2006) Enhancement of wind erosion by fire-induced water repellency. *Water Resources Research* **42(11)**: article W11422, https://doi.org/10.1029/2006WR004895.

Romero E and Simms PH (2008) Microstructure investigation in unsaturated soils: a review with special attention to contribution of mercury intrusion porosimetry and environmental scanning electron microscopy. *Geotechnical and Geological Engineering* **26(6)**: 705–727, http://doi.org/10.1007/978-1-4020-8819-3_8.

Romero E, Gens A and Lloret A (1999) Water permeability, water retention and microstructure of unsaturated compacted Boom clay. *Engineering Geology* **54(1–2)**: 117–127, http://doi.org/10.1016/S0013-7952(99)00067-8.

Salager S, El Youssoufi MS and Saix C (2010) Definition and experimental determination of a soil-water retention surface. *Canadian Geotechnical Journal* **47(6)**: 609–622, http://doi.org/10.1139/t09-123.

Seiphoori A, Ferrari A and Laloui L (2014) Water retention behaviour and microstructural evolution of MX-80 bentonite during wetting and drying cycles. *Géotechnique* **64(9)**: 721–734, http://doi.org/10.1680/geot.14.P.017.

Sheng D, Fredlund DG and Gens A (2008) A new modelling approach for unsaturated soils using independent stress variables. *Canadian Geotechnical Journal* **45(4)**: 511–534, http://doi.org/10.1139/T07-112.

Simms PH and Yanful EK (2001) Measurement and estimation of pore shrinkage and pore distribution in a clayey till during soil-water characteristic curve tests. *Canadian Geotechnical Journal* **38(4)**: 741–754, http://doi.org/10.1139/t01-014.

Sun WJ and Cui YJ (2017) Investigating the microstructure changes for silty soil during drying. *Géotechnique* **68(4)**: 1–4, http://doi.org/10.1680/jgeot.16.P.165.

Tang CS, Wang DY, Shi B and Li J (2016) Effect of wetting–drying cycles on profile mechanical behavior of soils with different initial conditions. *Catena* **139**: 105–116, http://doi.org/10.1016/j.catena.2015.12.015.

Wijaya M and Leong EC (2017) Modelling the effect of density on the unimodal soil-water characteristic curve. *Géotechnique* **67(7)**: 1–9, http://doi.org/10.1680/jgeot.15.P.270.

Yang D, Chen W, Wang L, Chen L and Wang W (2019) Experimental microscopic investigation of the cyclic swelling and shrinkage of a natural hard clay. *Géotechnique* **69(6)**: 481–488, http://doi.org/10.1680/jgeot.17.P.053.

Zhang C and Lu N (2020) Soil sorptive potential: its determination and predicting soil water density. *Journal of Geotechnical and Geoenvironmental Engineering* **146(1)**: article 04019118, http://doi.org/10.1061/(asce)gt.1943-5606.0002188.

Zhang J, Sun D, Zhou A and Jiang T (2016) Hydromechanical behaviour of expansive soils with different suctions and suction histories. *Canadian Geotechnical Journal* **53(1)**: 1–13, http://doi.org/10.1139/cgj-2014-0366.

Zhou AN, Sheng D and Carter JP (2012) Modelling the effect of initial density on soil-water characteristic curves. *Géotechnique* **62(8)**: 669–680, http://doi.org/10.1680/geot.10.P.120.

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