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Disintegration Mechanism and Swelling-Consolidation Characteristics of Saturated Disintegrated Carbonaceous Mudstone

--Manuscript Draft--

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Full Title:	Disintegration Mechanism and Swelling-Consolidation Characteristics of Saturated Disintegrated Carbonaceous Mudstone
Article Type:	SCI / ENG - Research Article
Section/Category:	ENG-Civil Engineering
Abstract:	Highway construction in southern China have revealed a massive distribution of carbonaceous mudstone. However, this mudstone is seldomly used as embankment fillers because of its significant disintegration upon wetting. Compared to bulk carbonaceous mudstone, small disintegrated carbonaceous mudstone (DCM) grains show less disintegration potential and may be applied to fill embankments in some cases. The purpose of this study is to reveal the mechanism behind the further disintegration of primarily DCM and investigate the swelling-consolidation characteristics of the DCM. Scanning electron microscopy (SEM) observations were performed on the compacted DCM specimens before and after wetting. The microstructural change and the disintegration mechanism of the DCM caused by wetting were analyzed. Then saturated free swelling tests and saturated consolidation tests were conducted to examine the influences of dry density and grain size range on the swelling and consolidation characteristics of the DCM. The results show that the disintegration of the DCM is owing to the swelling of hydrophilic clay minerals and softening and dissolving of inter-particle cementation. The free swelling deformation of the DCM increases with increasing dry density and decreasing grain size upon wetting. The DCM shows an increasing compression index as the consolidation pressure increases, which is related to its disintegrating nature. The settlement and compression index of the DCM reduce as an increase in dry density or the grain size. Therefore, the DCM of relatively large grain sizes and compacted at a higher dry density is recommended in filling highway embankments.
Response to Reviewers:	Responses to the Reviewers' Comments Manuscript Title: Disintegration Mechanism and Rebound-Consolidation Characteristics of Saturated Disintegrated Carbonaceous Mudstone Manuscript number: AJSE-D-21-08387 Dear Editor and Reviewers, Thank you for giving us the opportunity to revise our manuscript. The comments are all valuable and very helpful for improving the quality of the manuscript. We have considered all comments carefully and have made relevant corrections in the revised manuscript. All comments have been addressed and the changed contents in the manuscript are highlighted in red. We hope the revised manuscript will meet your expectations, and we are willing to answer any other questions you might have. Herein, we offer detailed and point-by-point responses to the reviewers' comments. COMMENTS Reviewer #1: This study aims to investigate the effect of wetting on disintegrated carbonaceous mudstone and the possibility of using it for highway constructions as embankment fillers because of its significant disintegration upon wetting. The text is written clearly. The adopted methodology is appropriate. Some issues should be improved to make the article's to be clearer. However, there are some comments for this study that need to be considered and implemented prior to the publication of this manuscript as follows. 1. The Title suggested to be changed to" Disintegration Mechanism, swelling and Consolidation Characteristics of Saturated Disintegrated Carbonaceous Mudstone", the swelling or expansion is more suitable than rebound due to existing of hydrophilic expansive clay minerals such as illite and muscovite. Response/Correction: The authors have considered the reviewer's comments and changed "Rebound" to "Swelling". The title after revision becomes "Disintegration Mechanism and Swelling-Consolidation Characteristics of Saturated Disintegrated Carbonaceous Mudstone".

2. In the abstract the abbreviation for " disintegrated carbonaceous mudstone (DCM)" is repeated, just for the first time write explanation for abbreviation.
Response/Correction: The authors have modified it.

3. On Page #7, lines 1 to 2" three ranges of grain sizes (0.075-2 mm, 0-0.075 mm and 0.075-1 mm)." the range "0-0.075 mm " is inappropriate should be written as 'less than 0.075 mm or <0.075 mm' it may be (<0.075 mm, 0.075 -1 mm and 1-2 mm) another way it should be draw the grain size distribution curve for the ranges.
Response/Correction: The authors have written all "0-0.075 mm as “less than 0.075 mm”.

4. on Page #7, line 56"saturated free rebound tests were performed" The saturated rebound test is not explained, or referred to a standard test method for doing it?
Response: The saturated rebound test had been explained in the second paragraph of Section 3.2. The main procedures of saturated free rebound tests are similar to those of unloaded swelling rate tests specified in the Chinese standard (JTG 3430-2020). The difference is that the unloaded swelling rate test focuses on the calculation of the swelling rate from the swelling deformation during the saturation of the soil sample; however, the saturated rebound test only focuses on the swelling deformation during the saturation of soil samples.
Correction: The authors have added a sentence to Section 3.2 to clarify that the saturated rebound test was similar to a standard test method: “The main procedures of saturation free swelling tests are similar to those of unloaded swelling rate tests specified in a Chinese technical code [27].”
References:
JTG 3430-2020. Test Methods of Soils for Highway Engineering. China Communications Press: Beijing, China. 2020.

5. On Page #12, line 58"evaporate " is used when the water evaporates due to high temperature but in this case, the water is pushed out due to pressure and void ratio reduction.
Response/Correction: The authors have removed “evaporate”.

6. change all "rebound " to a more suitable vocabulary such as "expansion, swelling, recompression".
Response/Correction: The authors have changed all “rebound” to “swelling”.

7. Fig.3, Grain size distribution curve of the DCM, usually drawn by a smooth curve passing through the average points, increase the number of sieves to get the more appropriate curve.
Response: Thanks for your comments. The authors have considered the reviewer's comments and corrected the grain size distribution curve (see Figs. S1 in responses to the reviewers file).

Correction: The authors have replaced the previous grain size distribution curve with the new curve that has smother shape (Fig. 3).

8. The vocabulary of "rebound" in Figs 9, 10, and 11 change to " swelling deformation or expansion'.
Response/Correction: The authors have changed "rebound" to "swelling deformation" in Figs. 9-11 (see Figs. S2-S4 in responses to the reviewers file).

9. Fig. 12. "(a) Compression vs time;" the expression should be corrected '(a) settlement or vertical deformation vs time;' also Fig. 12. part "(b) Compression vs stress;" the expression and the curve are incorrect; they should be revised.
Response/Correction: The authors have changed "Compression" to "Settlement" in both the captions and the pictures of Fig. 12 (see Fig. S5 in responses to the reviewers file). Accordingly, the corresponding texts in Section 4.3.1 have been corrected.

10. Fig. 13. "(a) Compression vs time;" the expression should be corrected '(a) settlement or vertical deformation vs time;' also Fig. 13. part "(b) Compression vs stress;" the expression and the curve are incorrect; they should be revised.

Response/Correction: The authors have changed "Compression" to "Settlement" in both the captions and the pictures of Fig. 13 (see Fig. S6 in responses to the reviewers file). Accordingly, the corresponding texts in Section 4.3.2 have been corrected.

Reviewer #2:
The disintegration process and rebound-consolidation features of the DCM are investigated experimentally in this research. After soaking the DCM specimens, SEM examinations were performed to investigate the material's disintegration mechanism. The effects of dry density and grain size on the deformation properties of the DCM were investigated using saturated free rebound tests and saturated consolidation tests. The swelling of hydrophilic clay minerals, as well as the softening and dissolving of inter-particle cementation, cause the DCM to disintegrate. The topic is of interest. The approach and experimental program as well as data analysis are sound leading to reliable conclusions. The text is well written, but language editing can improve the quality and is recommended. My main criticism towards this study is that:

1. The number of experiments used are not sufficient to make a conclusion. Therefore, I think authors should do more experimental works.
Response: This paper focused on the effect of dry density and particle size on the swelling and consolidation characteristics of DCM. Five levels of dry density (i.e., 1.68g/cm3, 1.78g/cm3, 1.88g/cm3, 1.98g/cm3, and 2.08g/cm3) which basically cover all the working conditions of highway embankment were considered. Three groups of particle sizes (i.e., less than 0.075mm, 0.075-1mm and 1-2mm) were selected. For each test case, three parallel specimens were prepared and tested. In the results section, we only provided the data of one representative specimen for each case. Considering the reviewer’s comment, we have plotted the data of all three specimens for each case in terms of peak deformations, see Fig. S7-S10 in responses to the reviewers file.

Correction: The test data of all specimens have been provided in forms of error bars, as shown in Figs. 9, 11-13.

2. Authors must also be able to justify the novelty of their research in a separate section like 'goals and objectives'.
Response/Correction: Thanks for your comments. The authors have greatly improved the last paragraph of the introduction section. After modifications, the novelty and objective of this study are better explained. Thus, the novelty and objective of this study are not repeated in a separate section.

3. There you should also describe the research limitations and contribution to the body of the literature.
Response: There are basically two major contributions of this study. First, the mechanism underlying the disintegration behavior of carbonaceous mudstone was revealed by a microscopic study. This allows us to understand why and how carbonaceous mudstone disintegrates. Second, the free swelling tests and consolidation tests were conducted on disintegrated carbonaceous mudstone specimens with different dry densities and particle sizes. The results provide us with the knowledge: what particle sizes and dry densities are the best choices when using disintegrated carbonaceous mudstone to fill highway embankment. These contributions have been described in the conclusion points. Regarding the limitations, the major one is that the particle sizes considered in this study are generally small and not wide enough. In addition, the environmental conditions that may have influences on the material’s behavior are not investigated.
Correction: The following sentences have been added to the last paragraph of the conclusion section to clarify the limitation and contribution of this study: “The findings of this study could provide guidance for the selection of filling materials in the design and construction of highway embankments using carbonaceous mudstone. Nevertheless, the maximum particle sizes of the DCM used in the tests were only 2 mm, which was a major limitation in this study. Further research could consider a wider range of particle sizes and explore the influences of various environmental factors (e.g., drying-wetting cycles, freeze-thaw cycles, and acid rainwater) on the disintegration behavior and swelling-consolidation characteristics of the DCM.”

	4. The Introduction is very long. It must be shorter and more straightforward. In addition, knowledge gap should be clarified clearer. Response/Correction: The authors have improved the introduction according to the reviewer’s comment. First, the authors shorten the introduction by describing in a straightforward the results of the studies that have been conducted by scholars. Then, a summary of the scholars' studies is summarized to clearly describe the knowledge gaps. Once again, we appreciate all your insightful comments. Thank you for taking the time and energy to help us improve the manuscript. Yours Sincerely, Ling Zeng, on behalf of all the authors Changsha University of Science & Technology Changsha 410114, China.

Disintegration Mechanism and Swelling-Consolidation Characteristics of Saturated Disintegrated Carbonaceous Mudstone

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Abstract: Highway constructions in southern China have revealed a massive distribution of carbonaceous mudstone. However, this mudstone is seldomly used as embankment fillers because of its significant disintegration upon wetting. Compared to bulk carbonaceous mudstone, small disintegrated carbonaceous mudstone (DCM) grains show less disintegration potential and may be applied to fill embankments in some cases. The purpose of this study is to reveal the mechanism behind the further disintegration of primarily DCM and investigate the swelling-consolidation characteristics of the DCM. Scanning electron microscopy (SEM) observations were performed on the compacted DCM specimens before and after wetting. The microstructural change and the disintegration mechanism of the DCM caused by wetting were analyzed. Then saturated free swelling tests and saturated consolidation tests were conducted to examine the influences of dry density and grain size range on the swelling and consolidation characteristics of the DCM. The results show that the disintegration of the DCM is owing to the swelling of hydrophilic clay minerals and softening and dissolving of inter-particle cementation. The free swelling deformation of the DCM increases with increasing dry density and decreasing grain size upon wetting. The DCM shows an increasing

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compression index as the consolidation pressure increases, which is related to its disintegrating nature. The settlement and compression index of the DCM reduce as an increase in dry density or the grain size. Therefore, the DCM of relatively large grain sizes and compacted at a higher dry density is recommended in filling highway embankments.

Keywords: Highway embankment • Carbonaceous mudstone • Disintegration • Swelling behavior • Consolidation • Microstructure

1 Introduction

Carbonaceous mudstone shows obvious softening and disintegration characteristics when exposed to water, and thus, it is often regarded as a poor fill material for highway embankments. Carbonaceous mudstone is widely distributed in China, especially in the southern and southwestern areas such as Guangxi, Guizhou, and Hunan. With the increasing attention to environmental protection, the full use of excavated soils to reduce spoil materials in highway construction becomes a general trend. Some studies have shown that the disintegrated carbonaceous mudstone (DCM) grains possess less disintegrating potential than the original bulk carbonaceous mudstone and may be used as fill materials [1]. It is particularly applicable to the construction of low-class highways where high-quality fill materials are scarce but carbonaceous mudstone is abundant [2,3]. However, uneven settlement and subsidence are still big concerns for the embankments made of the DCM under rainfall infiltration [4-6]. These problems begin with the construction phase. For this reason, it is necessary to systematically study the disintegration mechanism and the deformation characteristics of the DCM.

The disintegration characteristics of mudstone under dry, wet, hot, acidic, and other environmental conditions have received wide attention [2,4]. The entropy, fractal dimension, and grain size change were used to evaluate the disintegration characteristics of mudstone [7-10]. For example, Zhang et al. [11] was found that purple mudstone lost clay minerals and presented many surface pores and cracks while it was suffered from disintegration during dry-wet cycles. The disintegration occurred in the form of peeling onions. It is known that acidic and alkaline environments have significant effects on the disintegration characteristics of mudstone. Su et al. [12] was found that an increase in acidity promoted the disintegration of red-bed mudstone and had a significant impact on the shear strength of the mudstone. On the other hand, the alkaline environment inhibited the disintegration of red-bed mudstone and slightly reduced the shear strength. Rincon et al. [13] proposed the use of the horizontal/vertical spectrum ratio and image entropy to quantify the reliability of different degrees of the collapse of mudstone. Based on the clarification of the complex environment on mudstone disintegration behavior, some researchers have studied the softening and disintegration characteristics of carbonaceous mudstone in water environments. For example, Zeng et al. [14] stated that the mechanical properties of the modified DCM were greatly enhanced because the DCM grains were well bonded by cementitious materials and the soil structure was modified to be dense and stable. Most of the above studies were laboratory tests and did not involve practical engineering. Luo et al. [15] designed an automatic monitoring and early warning system to help prevent the hazards such as disintegration and instability of carbonaceous mudstone slopes. The authors successfully applied the system to the stability evaluation of a carbonaceous mudstone slope in practice.

Settlement is a type of common distress of road embankment, which is closely related to the deformation characteristics of fill materials [16-18]. It is well known that load is one of the main factors affecting the deformation characteristics of fillers. Lei et al. [19] indicated that the compression curves soft soil had two straight lines, which intersected at a yield stress, and the secondary compression characteristics depended on the applied stress and the initial void ratio. In addition, the deformation of the filler is also related to its physical properties and the environmental conditions in which it is deposited. Zeng et al. [2,4] and Fu et al. [5] examined the degree of compaction, moisture content and drying-wetting cycles on the deformation of the DCM. They reported that the deformation of the DCM was divided into two components, i.e., the compressive deformation and the wetting deformation. Tang et al. [20] found that the internal pores of modified DCM were filled with cement hydration products and the structure was gradually compacted, leading to its strength increase. Some scholars have established the relationship between compressive characteristics of filler and mechanical properties through consolidation tests. For example, Zeng et al. [2] developed a functional relationship between the shear strength and vertical deformation of the DCM. Ferrari et al. [21] designed a new experimental technique to investigate the consolidation behaviour of shales using an oedometer. An analytical method was formulated to analyze the shale consolidation behaviour as a function of the applied stress. Yang et al. [22] was found that the stress-strain curve of the transparent soft rock could be divided into three stages with an increase in consolidation pressure, and both the uniaxial compressive strength and elastic modulus of the transparent soft rock increased significantly. Li et al. [23] indicated that the deformation modulus weathered soft rocks increased with an increase in grain size, the relationship between unconfined compressive strength and moisture content was quadratic function, and the unconfined compressive strength increased linearly with dry density.

The review of the above studies indicates that the disintegrating characteristics and the mechanical behavior of soft rocks have received much attention. However, the disintegration mechanism and deformation characteristics of the DCM upon wetting are not well understood. The main objective of this study is to fill this research gap based on a series of microscopic and macroscopic laboratory tests. First, scanning electron microscopy (SEM) observations were conducted on the DCM specimens after wetting to examine the disintegration mechanism of the material. This result helps understand why and how carbonaceous mudstone disintegrates. Then, saturated free rebound tests and saturated consolidation tests were performed to investigate the influences of dry density and grain size range on the deformation characteristics of the DCM. The optimal dry density and grain size range of the DCM with minimum deformations are determined, which can provide guidance for the selection of filling materials in the design and construction of highway embankments using carbonaceous mudstone.

2. Material Properties

Undisturbed rock samples were taken from a carbonaceous mudstone cut slope at station K8+800 of the New Liu-Nan Expressway in Guangxi Zhuang Autonomous Region, China (Fig. 1). The rock samples were dark-brown with slablike or flaky bedding. The collected samples were disintegrated by loading-unloading and cyclic drying-wetting in the laboratory to obtain small DCM grains with sizes of less than 2 mm (Fig. 2) [2,5]. The grain size distribution curve is shown in Fig. 3. The physical properties of the DCM were tested via geotechnical tests. The test results are shown in Table 1. X-ray diffraction analysis indicated that quartz, kaolinite, illite, and muscovite are the main minerals in the DCM (Fig. 4). The main chemical compositions of the material are SiO_2, Al_2O_3, Fe_2O_3, K_2O and MgO [14].

3 Experimental Program

3.1 Microscopic tests

In this section, SEM observations were performed to reveal the mechanism underlying the further disintegration of the DCM grains upon wetting. The microscopic test schemes are shown in Table 2.

Two groups of cylindrical DCM specimens (S1 and S2) were prepared at two dry density levels

(2.08 and 1.68 g/cm^3), a moisture content (11%) and two ranges of grain sizes (0.075-2 mm and less than 0.075 mm). The diameter and height of the cylindrical specimens were 61.8 mm and 20 mm, respectively. The specimens were compacted in layers in a mold using the static compaction method [24]. The prepared specimens were then cut into small cuboid samples (length × width × height = 10mm × 10mm × 8mm) for SEM observation [25]. Afterward, epoxy resin was covered on the lateral surfaces of the small samples to reduce disturbances to the soil structure during sample transfers. In addition, the epoxy resin layer can serve as a location reference in SEM observation (Fig. 5). Before the first observation, the samples were polished with 1000-mesh sandpapers to produce smooth and flat top surfaces (10 mm×10 mm). The samples for SEM observation needs to be dried, but the oven-drying method will change the microstructure of the soil [2]. In this research, heating lamps were used to dehydrate the samples in the laboratory. The temperature of the sample surface remained at 38 ℃, which simulated the ground surface temperature in the studied area. When the dehydration was finished, the samples were submitted to SEM observations. The Zeiss evo10 SEM was used in the tests. To investigate the influence of wetting on the microstructure of the DCM, a wetting process was conducted on the samples after the first SEM observations. In the wetting process, a certain amount of distilled water (1 ml distilled water per 5 g sample) was sprayed on the surface of each sample, and then the samples were sealed with plastic films until uniform moisture was attained in the samples. After another dehydration, the samples were used to test the microstructure again by SEM. To facilitate a clear comparison between the results before wetting and after wetting, the same points on each sample were scanned in the first and second SEM observations (Fig. 5).

3.2 Saturated free swelling tests

Prior to the consolidation test, the DCM specimens must be saturated. Because the DCM is very sensitive to water, the saturation process may cause unexpected deformation of the specimen. However, this behavior of the DCM is not well understood. In this section, saturated free swelling tests were performed to investigate the swelling characteristics of the DCM due to saturation. The saturated free swelling test schemes are shown in Table 3.

The main procedures of saturation free swelling tests are similar to those of unloaded swelling rate tests specified in a Chinese technical code [27]. Six groups of the DCM specimens were prepared at five dry density levels (1.68-2.08 g/cm^3), a moisture content (11%) and three ranges of grain sizes (0.075-2 mm, less than 0.075 mm and 0.075-1 mm). The specimen preparation method is consistent with that used in the microscopic tests. Before the test, porous stones together with filter papers (diameter = 61.8 mm) were placed on the top and bottom of the specimen. The porous stones were used as referencing planes for displacement measurements. Then, the specimen was completely immersed in water (the water level was flush with the upper porous stone). During the test, the specimen was allowed to swelling freely in water with the vertical displacement recorded by the WD 5309-10 digital dial indicator in real-time. The digital dial indicator had a measurement range of 12.7 mm and a precision of 0.01 mm. The laboratory temperature was always kept at 25±1 ℃ during the test. After 48 h, if the vertical deformation of the specimen did not exceed 0.01 mm in a period of 12 h, the specimen was considered to be fully saturated, so the saturated free swelling test was ceased [26]. For comparison purposes, a specimen after vacuum saturation for 24 h was immediately used for saturated free swelling tests.

3.3 Saturated consolidation test

In this section, saturated consolidation tests were performed to investigate the consolidation characteristics of the saturated DCM. The saturated consolidation test schemes are shown in Table 4.

Six groups of the DCM specimens were prepared at five dry density levels (1.68-2.08 g/cm^3), a moisture content (11%) and three ranges of grain sizes (0.075-2 mm, less than 0.075 mm and 0.075-1 mm). The specimen preparation method was also the same as that used in the microscopic tests. After preparation, the specimens were saturated in a cylinder for 24 h under vacuum to ensure full saturation. The HM-1 resilient modulus meter was employed as the test instrument, and the WD 5309-10 digital dial indicator was used to record the specimen deformation. The saturated consolidation tests were performed strictly in accordance with the Chinese specification " Test Methods of Soils for Highway Engineering " (JTG 3430-2020). Five levels of vertical pressure (i.e., 25, 50, 100, 200, and 400 kPa) were applied to the specimen successively, and each level of pressure was maintained at least 24 h to allow the completion of consolidation. A settlement of 0.01 mm in 1 h was used as the criterion of consolidation completion [27]. During the test, the laboratory temperature remained at 25±1 ℃.

4 Results and Analysis

4.1 Disintegration and swelling mechanism of the DCM upon wetting

The previous experimental study showed that carbonaceous mudstone disintegrated strongly during the wetting process [5]. Although the materials used in this study were primarily disintegrated grains, they possessed further disintegrating potential.

Fig. 6 plots the SEM images with different magnifications of the same area of specimen S1 before and after wetting. Fig. 7 shows the images of specimen S2. It can be seen that the surface of the specimen polished with sandpapers is smooth and flat before wetting. However, the specimen surface rises obviously and becomes very rough after wetting. Before wetting, the morphology of the DCM specimen is mainly characterized by blocky and flaky structures. The DCM grains are tightly arranged and bonded with only a few tiny primary pores of 2-10 μm. After wetting, the arrangement of the

DCM grains becomes loose and an obvious dislocation between the grains occurs. Moreover, the primary pores are enlarged and many new pores of 5-50 μm appear.

This is because, during the wetting process, water penetrates into the interior of the specimen via the primary pores on the surface, which leads to an increase in the moisture content of the specimen. Since the DCM contains a large number of hydrophilic clay minerals such as illite and muscovite (Fig. 4), the growth of moisture content will cause the clay minerals to expand. Consequently, the volume of the specimen increases, showing a bulge shape on the surface (Fig. 8). The uneven swelling of the material due to a random distribution of clay minerals inevitably induces tensile stress in the material. When the tensile stress exceeds the tensile strength of the material, new pores and even cracks appear in local areas. In addition, the water penetrated into the specimen will serve as a medium for the hydration reaction (Eq. (1)) of the illite in the weakly acidic water environment due to the dissolving of carbon dioxide [28,29]. The hydration reaction not only increases the original volume of mineral particles but also softens and even dissolves inter-particle cementation. For this reason, some clay minerals fall off from the DCM grains, producing a loose soil structure with many large pores. This phenomenon is characterized by the disintegration of the DCM from a macroscopic point of view.

$$K_{0.9}Al_{2.9}Si_{3.1}O_{10}(OH)_2+nH_2O \xrightarrow{\text{the weakly acidic water environment}} K_{0.9}Al_{2.9}Si_{3.1}O_{10}(OH)_2\bullet nH_2O \quad (1)$$

4.2 Free swelling characteristics of saturated DCM

4.2.1 Effect of dry density

Fig. 9 shows the free swelling characteristics of saturated DCM specimens with different dry densities prepared at a moisture content of 11%. Generally, the swelling deformations of the DCM specimens first rise sharply (first 0.5 h), then increase slowly (0.5-8 h), and finally reach plateaus (after 8 h). Within an immersion duration of 0.5 h in water, air bubbles can be clearly observed, indicating that the air in the internal pores of the specimen is discharged by the water infiltrated into the specimen. As the immersion duration increases, the moisture content of the specimen goes on increasing, and the specimen gradually changes from an unsaturated state to a saturated state. During this process, hydrophilic clay minerals expand and some large DCM grains are gradually broken down into a number of small grains, resulting in a rearrangement of the DCM grains and an increasing void of the material. Consequently, the specimen exhibits a swelling deformation until reaching a stable state.

In addition, as the dry density increases, the swelling speed of the specimen becomes faster; at the same time, the time is longer for the swelling deformation to stabilize, and the peak swelling deformation is greater. For example, the deformation of the specimen with a dry density of 1.68 g/cm^3 is 0.30 mm (90% of the peak swelling deformation) at 0.5 h, while that of the specimen with a dry density of 2.08 g/cm^3 can reach 0.98 mm (60% of the peak swelling deformation) at 0.5 h. The greater the dry density is, the smaller the volume of air phase in the specimen is, but the more the volume of the solid phase is. In the process of bubble expelling (water infiltration), a specimen with a higher dry density contains more hydrophilic clay minerals, and the water-expansion is more significant. As the differential expansion inside the specimen induces grain disintegration, the connection between mineral particles is weakened. The combined effect of the force generated by the upward discharge of the air bubbles and the buoyancy of the water makes the DCM grains move upwards. Thus, the gap between the grains further increases, causing the specimen to swell and deform. As the duration increases, the specimen changes from an unsaturated state to a saturated state, the rearrangement of the DCM grains tends to stabilize, and the soil skeleton no longer changes. Fig. 10 shows the swelling curves of a DCM specimen immediately after preparation and a DCM specimen after vacuum saturation. The two specimens had the same dry density of 2.08 g/cm^3 and initial moisture content of 11%. It can be seen that the specimen without saturation swellings slightly after the preparation; the swelling deformation increases in a short period of time and then quickly reaches a stable value of 0.01 mm. By contrast, the saturated DCM specimen exhibits a more obvious swelling deformation. The deformation first increases sharply until meeting a peak value of 0.28 mm and then slowly decreases with a final value of 0.18 mm. The reason is that when the specimen is saturated under vacuum conditions, water penetrates into the specimen through the porous stone and filter paper, while the air in the pores of the specimen is discharged. At the same time, the hydrophilic clay minerals in the specimen hydrate and expand. The DCM grains are constrained by the stacked saturator to squeeze each other. When the specimen is taken out of the saturator, the vertical deformation constraint is lifted, and the DCM grains will move reversely under the inter-grain squeezing force, causing the soil skeleton to be expanded and deformed. As time goes on, the water on the specimen surface gradually evaporates. The hydrophilic clay minerals in the specimen will shrink in volume due to the loss of water, resulting in a rearrangement of soil grains and a reduction of inter-grain gaps [30-32].

4.2.2 Effect of grain size range

Fig. 11 shows the free swelling curves of the DCM specimens with different grain size ranges at a dry density of 1.78 g/cm^3 and a moisture content of 11%. It can be seen that the swelling deformations of the DCM specimens with different grain size ranges are consistent. Generally, the peak swelling deformation, the swelling speed and the time for stabilization of the specimen of small grain sizes are much greater than those of the specimen of large grain sizes. The deformation of the specimen of large grain sizes (0.075-2 mm) can reach 90% of the peak swelling deformation (0.91 mm) within 0.5 h. By contrast, the deformation of the deformation of the specimen of medium size grains (0.075-1 mm) can reach 87% of the peak swelling deformation (1.14 mm) in 0.5 h, the specimen of small size grains (less than 0.075 mm) can reach 78% of the peak swelling deformation (3.84 mm) in 0.5 h. This is because although the internal pore volume of the specimens with different initial grain sizes is the same, the specimen of small grain sizes has a large number of fine pores due to their small grains. During the gradual saturation process of the specimen of small grain sizes, water penetrates into the specimen from the surface pores, and the water squeezes out the air in the specimen and fills the pores. As the contact area between the grains and water increases, the effect of water-rock interaction is more significant. The buoyancy of the grains and the discharge of air bubbles increase the upward force on the grains, and the tendency of the grains to move is intensified. As a result, the gap between the DCM grains gradually increases, and the flow of water inside and outside the specimen accelerates. The buoyancy of the grains and the interaction force caused by the discharge of bubbles on the grains go on increasing.

4.3 Consolidation characteristics of saturated DCM

4.3.1 Effect of dry density

Fig. 12(a) and (b) show the settlements of saturated DCM specimens at different dry densities with time and consolidation pressure.

It is observed that the settlements of saturated DCM specimens with different dry densities are positive and show similar changing tendencies. At the moment when each level of consolidation pressure is applied, the settlement of the specimen undergoes a sudden change to produce a large deformation. As the deformation increases, the speed gradually falls down, and the deformation tends to be stable. Moreover, the settlement increases with increasing consolidation pressure. With an increase in dry density, the settlement of the specimen under each consolidation pressure decreases.

The reason is that due to the strong fluidity of water, the water in the pores of the specimen is easily extruded under the consolidation pressure. Meanwhile, as the hydrophilic clay minerals such as illite and muscovite lose water, the adsorbed water film on the surface becomes thin and easy to shrink unevenly, which causes the original cracks to expand and produce new cracks. Therefore, a crisscross and fragile crack network is formed, and the grains are broken under the consolidation pressure. Disintegration is significant, the grain structure is broken, and disintegrated grains changes from block or sheet to slender needle shape. Then the specimen is settled. This process is particularly significant when the consolidation pressure is applied. The settlement gradually increases and finally stabilizes with time under each level of consolidation pressure. As the applied consolidation pressure increases, its effect on the specimen becomes stronger; meanwhile, the effect of pore water seepage, the reduction of inter-grain gaps, and the rearrangement of grains become more significant. Therefore, the deformation is greater. It can be seen that as the dry density of the specimen increases, the volume of internal pore water and the settlements produced by each level of consolidation pressure become smaller.

Fig. 12 (c) and (d) are the curves of the void ratio and compression index of saturated DCM specimens with different dry densities as a function of consolidation pressure. It shows that the void ratios of saturated DCM specimens with different dry densities decrease with the increase in consolidation pressure, showing a rapid decrease first and then a slow decrease. At a lower dry density, the reduction of the void ratio of the specimen is larger as the consolidation pressure increases. The reason is that the smaller the initial dry density is, the smaller the volume of solid phase is, and the larger the volume of pores is when preparing the specimen. Since the specimen is fully saturated, all pores are filled with water. During consolidation, the water in large pores is drained quickly and the specimen with a larger pore volume is easier to be compressed under the pressure. In this process, large pores become smaller and the pore number reduces, leading to a larger reduction in soil void ratio. The compression index of saturated DCM specimens shows an increasing trend with the increase in consolidation pressure regardless of the dry density. This is because the disintegration of DCM grains caused by differential wetting-expansion of clay minerals is more significant under a higher consolidation pressure. The disintegrated grains can be re-cemented, but the strength of the cementation matter is significantly reduced and the ability to resist external forces is weakened [32]. Therefore, with the increase of consolidation pressure, the compression index of DCM specimens further increases [2,3]. However, at a large dry density (e.g., ρ_d > 1.88 g/cm^3), the slope of the compression index gradually decreases with the growth in consolidation pressure.

4.3.2 Effect of grain size range

Fig. 13(a) and (b) shows the settlement curves of specimens of different grain size ranges at a dry density of 1.78 g/cm^3 and a moisture content of 11%. It is noted that the settlements of saturated DCM specimens with different grain sizes exhibit similar tendencies. The settlement increases with the increase of consolidation pressure. The specimen of small grain sizes is more sensitive to the effect of consolidation pressure, and its settlement is larger than that of the specimen of large grain sizes. The specimens with different grain sizes have identical dry density, moisture content and initial void ratio; meanwhile, the masses of dry soil and water in each specimen are the same in the specimen preparation process. However, there are many small pores inside the specimen of small grain sizes, the contact area between the DCM grains and water increases, and the water blocking area decreases. Numerous small pores provide a convenient channel for the loss of water, causing the hydrophilic clay minerals in the specimen to shrink and crack severely. The primary bonding force between the grains drops sharply, and the consolidation pressure aggravates the breakage of the DCM grains [2]. Therefore, the settlement is more significant for the specimen with smaller grain sizes.

Fig. 13(c) and (d) are the curves of void ratio and compression index of saturated DCM specimens with different grain size ranges at a dry density of 1.78 g/cm^3 and a moisture content of 11%. It shows that the void ratios of saturated DCM specimens with different grain size ranges decrease with the increase of consolidation pressure. With an increase in the consolidation pressure, the change in void ratio of the specimen of small grain sizes is larger than that of the specimen of large grain sizes. Combined with Fig. 11, it can be seen that the saturated swelling deformation of the specimen with small grain sizes is much larger than that of the specimen with large grain sizes. When the first consolidation pressure is applied, the specimen with small grain sizes is more easily compressed. This is because the smaller the grain size is, the larger specific surface area is, and thus the faster the hydration rate of hydrophilic minerals is, so the decrease of void ratio are greater than that of the specimen with large grain sizes. References [32-34] reported that sand grains play a certain role in the framework of soil, and the compression characteristics of soil decrease with an increase in sand content. Because the sand content of the specimen of large grain sizes is much higher than that of the specimen of small grain sizes, the compressibility of the specimen of large grain sizes are smaller. As the grain size decreases, the increasing speed and amplitude of the compression index reduce gradually. The DCM grains contain a large amount of illite and muscovite with strong water absorption and expansion, leading to hydration disintegration of the DCM grains, which will increase under a higher consolidation pressure. Therefore, the compression indexes of all saturated DCM specimens increase with an increase in consolidation pressure.

5 Conclusion

In this paper, SEM observations were performed on the DCM specimens after wetting to examine the disintegration mechanism of the material. Then, saturated free swelling tests and saturated consolidation tests were conducted to investigate the influences of dry density and grain size range on the deformation of the DCM. The following conclusions can be drawn:

1. The DCM contains numerous hydrophilic clay minerals such as muscovite and illite with strong water-absorbing swelling properties. Pore water provides a medium for the chemical reactions of the minerals in the weakly acidic water environment where carbon dioxide is dissolved. The reaction causes uneven expansion of the specimen volume. The massive and sheet-like structures of the DCM disintegrate into slender needle-like structures, and the clay minerals fall off the structure surface on wetting.

2. The swelling deformation of the DCM first increases sharply, then increases slowly, and finally reaches plateaus upon wetting. As the dry density increases, the swelling speed of the specimen increases; at the same time, the time is longer for the swelling deformation to stabilize, and the peak swelling deformation is greater at a larger dry density. The peak swelling deformation, swelling speed and stabilizing time of the specimen of small grain sizes are much greater than those of the specimen of large grain sizes.

3. The settlement, the void ratio, and compression index of the DCM significantly reduce as the dry density increases. Moreover, the specimen of small grain sizes is more sensitive to the effect of consolidation pressure. The settlement and compression index of the specimen of small grain sizes are larger than those of the specimen of large grain sizes. The compression index of the DCM continuously increases with increasing consolidation pressure, which is related to the disintegrating natural of the material.

4. The DCM of small grains, particularly that at a high dry density, may cause swelling to a highway embankment during construction. However, this swelling is beneficial to offset the settlement of the embankment due to soil consolidation. Since the DCM of small grains will show large consolidation deformation, it is recommended to select the DCM of larger grains and compact at a larger dry density when it is used to fill highway embankments.

The findings of this study could provide guidance for the selection of filling materials in the design and construction of highway embankments using carbonaceous mudstone. Nevertheless, the maximum particle sizes of the DCM used in the tests were only 2 mm, which was a major limitation in this study. Further research could consider a wider range of particle sizes and explore the influences of various environmental factors (e.g., drying-wetting cycles, freeze-thaw cycles, and acid rainwater) on the disintegration behavior and swelling-consolidation characteristics of the DCM.

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Statements and Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. He, Z.M.; Liu, X.Q.; Huang, K.; Xiong, J.P.: Seepage and Dynamic Characteristics of Carbonaceous Mudstone Coarse-Grained Soil Embankment with Different Gradations. Adv. Civ. Eng. **2021**, 4436942 (2021). https://doi.org/10.1155/2021/4436942
2. Zeng, L.; Yu, H.C.; Liu, J.; Gao, Q.F.; Bian, H.B.: Mechanical behaviour of disintegrated carbonaceous mudstone under stress and cyclic drying/wetting. Constr. Build. Mater. **282**, 122656 (2021). https://doi.org/10.1016/j.conbuildmat.2021.122656.
3. Zeng, L.; Zha, H.Y.; Gao, Q.F.: Optimal design of mixing ratios of modifiers for disintegrated carbonaceous mudstone. Geomech. Eng. **26**, 401-413 (2021). https://doi.org/10.1166/jnn.2020.18486.
4. Zeng, L.; Luo, J.T.; Gao, Q.F.; Bian, H.B.: Disintegration characteristics and mechanisms of carbonaceous mudstone subjected to load and cyclic drying-wetting. J. Mater Civil Eng. (2021). 10.1061/(ASCE)MT.1943-5533.0003817.
5. Fu, H.Y.; Liu, J.; Zeng, L.; Xiao, L.Y.; Hou, P.: Disintegration Characteristics of Carbonaceous Mudstone Under Loading and Wet-dry Cycles. China. J. Highw. Transp. **32**, 22-31 (2019) (in Chinese)
6. Liu, X.X.; Deng, Z.J.; Chen, L.; Wang, W.W.; Zhang, Z.: Simulation analysis of wetting deformation of carbonaceous mudstone cutting slope. J. Transport. Sci. Eng. 37, 1-6 (2021) (in Chinese)
7. Wang, Y.; Qiao, Q.N.; Li, J.L.: Effect of wet-dry cycles on disintegration characteristics of clay-bearing sandstone with uf cracks. Period. Polytech-civ. (2020). https://doi.org/10.3311/PPci.15124.
8. Zhao, J.X.; Lu, C.H.; Deng, L.M.; Liu, G.C.: Impacts of simulated acid solution on the disintegration and cation release of purple rock (mudstone) in southwest china. Geomorphology. **316**, 35-43(2018). https://doi.org/10.1016/j.geomorph.2018.05.009.
9. Zhang, D.; Chen, A.Q.; Liu, G.C.: Laboratory Investigation of Disintegration Characteristics of Purple Mudstone under Different Hydrothermal Conditions. J. Mt. Sci. **9**, 127-136 (2012). https://doi.org/10.1007/s11629-012-2204-1.
10. Jiang, Q.; Cui, J.; Feng, X.T.; Jiang, Y.J.: Application of computerized tomographic scanning to the study of water-induced weakening of mudstone. B. Eng. Geol. Environ. **73**, 1293-1301 (2014). https://doi.org/10.1007/s10064-014-0597-5.
11. Zhang, Z.H.; Liu, W.; Han, L.; Chen, X.C.: Disintegration behavior of strongly weathered purple mudstone in drawdown area of three gorges reservoir, china. Geomorphology. **315**, 68-79 (2018). https://doi.org/10.1016/j.geomorph.2018.05.008.
12. Su, X.X.; Tang, H.M.; Huang, L.; Shen, P.W.: The role of pH in red-stratum mudstone disintegration in the three gorges reservoir area, china, and the associated micromechanisms. Eng. Geol. **279**, 105873 (2020). https://doi.org/10.1016/j.enggeo.2020.105873.
13. Rincon, O.; Shakoor, A.; Ocampo, M.: Investigating the reliability of H/V spectral ratio and image entropy for quantifying the degree of disintegration of weak rocks. Eng. Geol. **207**,115-128 (2016). https://doi.org/10.1016/j.enggeo.2016.04.020.
14. Zeng, L.; Yu, H.C.; Gao, Q.F.; Bian, H.B.: Mechanical behavior and microstructural mechanism of improved disintegrated carbonaceous mudstone. J. Cent. South Univ. **27**, 1992-2002 (2020). https://doi.org/10.1007/s11771-020-4425-8.
15. Luo, J.H.; Mi, D.C.; Huang, H.F.; Zhang, T.: Intelligent monitoring, stability evaluation, and landslide treatment of a carbonaceous mudstone and shale slope in guangxi, china. Int. J. Safety Security Eng. **10**, 373-379 (2020). https://doi.org/10.18280/ijsse.100309.
16. Kamiya, N.; Zhang, F.; Fukuoka, J.; Kato, Y.; Lin, W.R.: Strain Softening of Siltstones in Consolidation Process. Mater. Trans. **61**, 1096-1101 (2020). https://doi.org/10.2320/matertrans.Z-M2020818.

17. Hadiseh, M.; Rassoul, A.: Mechanical behavior of salt rock under uniaxial compression and creep tests. Int. J. Rock Mech. Min. **110**, 19-27 (2018). https://doi.org/10.1016/j.ijrmms.2018.07.006.
18. Gutierrez, M.; Katsuki, D.; Tutuncu, A.: Determination of the continuous stress-dependent permeability. compressibility and poroelasticity of shale. Mar. Petrol. Geol. **68**, 614-628 (2014). https://doi.org/10.1016/j.marpetgeo.2014.12.002.
19. Lei, H.Y.; Wang, X.H.; Chen, L.; Huang, M.S.; Han, J.: Compression characteristics of ultra-soft clays subjected to simulated staged preloading. KSCE J. Civ. Eng. **20**, 718-728 (2016). https://doi.org/10.1007/s12205-015-0343-y.
20. Tang, J.; Ding, Q.L.: Analysis of strength characteristics and microscopic mechanism of modified disintegrated carbonaceous mudstone. J. Transport. Sci. Eng. 37, 13-18 (2021) (in Chinese)
21. Ferrari, V.; Favero, L.; Laloui.: One-dimensional compression and consolidation of shales. Int. J. Rock Mech. Min. **88**, 286-300 (2016). https://doi.org/10.1016/j.ijrmms.2016.07.030.
22. Yang, X.; Jin, G.; Huang, M.; Tang, K.: Material preparation and mechanical properties of transparent soil and soft rock for model tests. Arab. J. Geosci. **13**, (2020). https://doi.org/10.1007/s12517-020-05325-7.
23. Li, X.Q.; Jin, Q.P.: Compacting Deformation Engineering Characteristics of Weathered Soft Rock Mixture in Subgrade. J. China Univ. Geosci. **19**, 298-306 (2008). https://doi.org/10.1016/S1002-0705(08)60048-5.
24. Zeng, L.; Luo, J.T.; Hou, P.; Bian, H.B.: Crack development and strength characteristics of pre-disintegrated carbonaceous mudstone under dry-wet cycles. China J. Highw. Transp. **33**, 1-11 (2020) (in Chinese). https://doi.org/10.3969/j.issn.1001-7372.2020.09.001
25. Gao, Q.F.; Zeng, L.; Shi, Z.N.; Zhang, R.: Evolution of unsaturated shear strength and microstructure of a compacted silty clay on wetting paths. Int. J. Geomech. (2021). https://doi.org/10.1061/(ASCE)GM.1943-5622.0002207.
26. JTG E41-2005. Test Methods of Rock for Highway Engineering. China Communications Press: Beijing, China. 2005.
27. JTG 3430-2020. Test Methods of Soils for Highway Engineering. China Communications Press: Beijing, China. 2020.
28. Shoedarto, RM.; Tada, Y.; Kashiwaya, K.; Koike, K.; Iskandar, I.: Specifying recharge zones and mechanisms of the transitional geothermal field through hydrogen and oxygen isotope analyses with consideration of water-rock interaction. Geothermics. **86**, 101797 (2020). https://doi.org/10.1016/j.geothermics.2019.101797.
29. Zhang, K.; Gao, J.; Men, D.P.; Zhao, X.Y.; Wu, S.S.: Insight into the heavy metal binding properties of dissolved organic matter in mine water affected by water-rock interaction of coal seam goaf. Chemosphere. **265**, 129134 (2020)
30. Li, X.M.; Kong, L.W.; Guo, A.G.; Liu, Y.; Liu, X.D.: Experimental research on shear strength of expansive soil under wetting-drying cycles based on wrapping method. Rock Soil Mech. **35**, 675-682 (2014) (in Chinese). https://doi.org/10.1016/j.chemosphere.2020.129134.
31. Sun, M.Q.; Wang, Q.; Niu, C.C.; Sun, T.: Research on the one-dimensional rheological consolidation theory that considers secondary consolidation effect. J. Comput. Theor. Nanos. **13**, 1136-1146 (2016). https://doi.org/10.1166/jctn.2016.5024.
32. Chai, Z.Y.; Zhang, Y.T.; Zhang, X.Y.: Experimental investigations on correlation with slake durability and mineral composition of mudstone. J. China Coal Society. **40**, 1188-1193 (2015) (in Chinese). https://doi.org/10.13225lj.cnki.jccs.2014.0897.
33. Wu, Y.J.; Li, J.P.; Jiang, H.B.; Kong G.Q.: Consolidation and Permeability Characteristics of Transparent Clay with Different Grain Composition. J. Northeastern Univ. **41**, 875-880 (2020) (in Chinese). https://doi.org/10.12068/jissn.1005-3026.2020.06.020.
34. Yang, S.; Cheng, Y.J.; Wu, J.H.; Lu, T.H.: Influence of Coarse Granular Soil grain size on the Strength and the Compression Characteristic. J. Yunnan Agr. Univ. **29**, 562-565 (2014) (in Chinese). https://doi.org/10.3969/j.issn.1004-390X(n).2014.04.018.