Disintegration Mechanism and Hydrogeochemical Processes of Red-Bed Soft Rock Under Drying-Wetting Cycle

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Disintegration mechanism and hydrogeochemical processes of red-bed soft rock under drying-wetting cycle

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Abstract: Red-bed soft rock in the drawdown area on bank slopes of landslide easily disintegrates upon exposure to water, and its properties experience comprehensive deterioration, which will cause bank slope instability. To better study disintegration mechanism of the red-bed soft rock, a series of laboratory tests were conducted in this paper to investigate the disintegration characteristics, durability and hydrogeochemical process of red-bed argillaceous siltstone under drying-wetting cyclic conditions. Experimental results showed that, with increasing number of drying-wetting cycles, red-bed argillaceous siltstone gradually disintegrated, from initial appearing the cracks on the surface of the samples to large particles gradually breaking up into small fragments. Significant changes in grain size distribution, and the durability index of the samples progressively decreased. Microstructural analysis showed that the size and distribution of pores and cracks in the sample surface significantly increased, such that the sample surface became disordered and complicated. Notable changed in concentrations of ions in the soaking solutions indicated continuous mineral dissolution and loss during the cyclic drying-wetting. Based on the results obtained from the experiment, it is concluded that the disintegration of samples undergoing drying-wetting cycles was the result of the synergistic action of water and temperature. To be specific, the dissolution of calcite, albite, gypsum, montmorillonite and kaolinite during the wetting procedure, which promotes the decrease in mineral content and increases in pores and cracks. The increases in temperature and the dehydration shrinkage of sample during the drying procedure accelerated the disintegration of the samples.

Keywords: Red-bed argillaceous siltstone; Disintegration mechanism; Drying-wetting
cycles; Hydrogeochemical process, Microstructural analysis.

1 Introduction

Red-bed soft rock is a sedimentary rock of the Triassic, Jurassic, and Cretaceous systems, with red, purple and dark red colors, and it is a typical soft rock, which including sandstone, siltstone, shale, and mudstone. In addition, red-bed soft rock is a kind of multiphase composite with microscopic pores and cracks result in these rocks being highly vulnerable to the effects of water. Resulting in disintegration with water, which can severely affects the stability of rock masses and result in problems in engineering construction (Molina et al. 2011). Additionally, red-bed soft rock is widely distributed across the globe, and is often encountered in major engineering construction projects (Rincon et al. 2016). Therefore, the disintegration characteristics of red-bed soft rock are worthy of thorough investigation, and have attracted extensive attention during the past decade (Kurlenya and Oparin 1996; Doostmohammadi et al. 2009; Selen et al. 2019).

Disintegration is a physical and chemical weathering process that is affected by many factors. Phienwej (1995) found that disintegration was caused mainly by changes in the water content of rock. Similar results were found by Newman (1983) and Liu et al. (2000), the results showed that disintegration of mudstone was caused by the presence of water, which reduced the degree of cementation among mineral particles. Youn and Tonon (2010) considered that the disintegration is the structural degradation of an intact mass into smaller particles due to a change in water content. Zhang et al. (2012) and Liang (2016) indicated that high temperature accelerated the disintegration
of mudstone during the tests. In addition, as the significant impact parameters in
disintegration, the mineral composition and microstructure of rock have been widely
investigated in previous studies (Huang et al., 2020; Hua et al., 2015; Ghabadi et al.
2014; Hajdarwish et al. 2013; Dhakal et al. 2002). According to the studies conducted
by Deng et al. (2016) and Pham et al. (2007), the propagation of macro-cracks caused
by water was closely related to the material composition of mudstone. Gökceoğlu et al.
(2000) and Pejon et al. (1998) investigated the influence of mineralogical composition
on durability. The experiments proved that as the amount of clay minerals gradually
increases, the durability of the soft rock decreased. Tests conducted by Bryson et al.
(2012), Weng and Li (2012) and Cantón et al. (2001) also found that increases in cracks
and clay minerals resulted in a more complete disintegration of rocks.

Water-weakening effects on soft rocks have been a major research topic in rock
engineering field due to high practical values, and numerous theoretical and
experimental studies have been conducted to reveal the relationships between the
stability of rock masses and their disintegration properties quantitatively. Franklin and
Chandra (1972) investigated the process of disintegration under drying and wetting
conditions and proposed the first durability test. This was subsequently standardized by
both the American Society for Testing and Materials (ASTM 2013) and the
International Society for Rock Mechanics (ISRM 2007). The resulting durability index
is an important indicator of the disintegration behavior of rocks. Erguler and Ulusay
(2009) and Gautam and Shakoor (2016) investigated the difference in the disintegration
behavior under laboratory and natural climatic conditions and found that the durability
index of specimens under laboratory conditions is consistent with that under natural climatic conditions. Research performed by Sadisun et al. (2005) and Zhou et al. (2017) pointed out that the durability index, density and compressive strength decreased with an increase in the number of wetting and drying cycles, and the cyclic wetting and drying process is considered to be one of the main processes that can cause degradation and deterioration of rock material.

As for the red-bed soft rock in the drawdown area on bank slopes of landslide, the cyclic drying-wetting process lasts for a long time during the course of reservoir operation and has its own distinct drying-wetting alternating regime (Zhang et al. 2018). Additionally, the disintegration of the red-bed soft rock in the drawdown area is a typical physical and chemical process under cyclic drying-wetting conditions. Although the disintegration of soft rock has attracted extensive attention in previous research, most studies have focused mainly on the disintegration behavior, scarcely any have paid attention to the chemical process of the disintegration and disintegration mechanism (Kyu and Chernov 1998; Sun et al. 2009; Qian et al. 2009). In this study, red-bed argillaceous siltstone were selected to investigate the disintegration characteristics, durability and microstructure characteristics of the red-bed argillaceous siltstone after undergoing various drying-wetting cycles. In the meantime, the evolution of the ion concentration in the aqueous solution during the process of drying-wetting cycles were also analyzed, and the chemical disintegration mechanism of red-bed argillaceous siltstone was comprehensively investigated, which provides theoretical guidance for chemical modification of red-bed landslides in the future.
2 Materials and methods

2.1 Materials

The tested samples with similar close masses, geometric shapes and identical mineral compositions, were red-bed argillaceous siltstone of the Tertiary Wanghudun Formation (E1w). They were collected from Tongcheng, Anhui Province, China. The basic physical properties of the red-bed argillaceous siltstone, including its density, water content, and bulk density, are presented in Table 1. The X-ray diffraction (XRD) results of the samples are testing are illustrated in Fig. 1 and Table 2. It can be observed that the main mineral components of the tested rocks were quartz (44.29%), muscovite (3.97%), calcite (10.47%), albite (17.35%), gypsum (5.09%), and the clay mineral content was 18.82%. In addition, the major chemical components of the tested rock, determined using the X-ray fluorescence (XRF) technique, are listed in Fig. 2. As can be observed, the main chemical components of the tested samples were silicon (Si, 57.82%), aluminum (Al, 16.98%), iron (Fe, 5.21%), sodium (Na, 0.53%), and magnesium (Mg, 3.65%), along with potassium (K, 4.47%) and calcium (Ca, 9.26%).

2.2 Experimental methods

2.2.1 Disintegration experiment

The disintegration experiment, as described by the ASTM and the ISRM, was performed to assess the disintegration behavior of red-bed argillaceous siltstone in the laboratory. In this study, ten cycles were designed and performed to ensure that all the samples completely disintegrated. In general, a single drying-wetting cycle was divided into two processes: drying (from wet to dry state) and wetting (from dry to wet state).
In each cycle, the samples were submerged in deionized water for 24h to wet state and then, removed and dried in an oven at 105°C for 24 h according to ASTM D4373-14 (2014).

In this study, 20 samples, were selected for the experiments. A total of 10 drying-wetting cycles were carried out for each sample, and the disintegration characteristics of the samples after each cycle was observed and recorded. The disintegration products were sieved by 5, 2, 0.5, and 0.25 mm standard sieves, and the masses and quantities of grains with different particle sizes, were counted after the end of each cycle. The grain-size distribution curves of the disintegration products are useful data for evaluating physical disintegration characteristics of rocks (Czerewko and Cripps 2001; Erguler and Shakoor 2009; Gautam and Shakoor 2013; Zhang et al., 2012; Wu et al. 2010).

2.2.2 Scanning electron microscopy

The samples, subjected to their designated numbers of drying-wetting cycles were broken into small pieces with an approximate size of 5 mm × 5 mm × 5 mm. Pretreatment measures were applied to the samples. First, a hairbrush was used to clean their surface, then they were freeze-dried in an Alpha 1-4 LDplus freeze dryer for 24 h, and finally, vacuum metal spraying technology was used to obtain sufficient conductivity. Morphology observations were simultaneously conducted using a JSM-6490LV scanning electron microscope (SEM) (Devarapalli et al. 2017; Tavanaei and Salehi 2015).

2.2.3 Aqueous solution detection
Different chemical processes can occur during the drying-wetting cycles, which include dissolution/precipitation, ion exchange processes, oxidation, and reduction. Minerals present in rock will partially or completely dissolve in water according to its resistance to chemical weathering. During these chemical interaction processes, the following changes may occur in the system: (1) increase or decrease in the concentration of ions in water, (2) the mobility of the dissolved constituents may be affected (Jalali and Khanlari 2008).

After the samples subjected to the drying-wetting cycles, various ions appeared in the solution, and the concentrations of ions varied with the number of drying-wetting cycles. In this study, the cations and anions were determined in the laboratory after all the samples were filtered using 0.45 μm Millipore membrane filters. The concentration of cations in the solution was measured through inductively coupled plasma mass spectrometry (ICP-MS), and the content of anions was measured using ion chromatography (IC).

All the experiments are performed at an ambient temperature of 20±0.1°C.

3 Experimental results

3.1 Disintegration characteristics

The disintegration characteristics and schematic diagram of samples subjected to different cycles of drying-wetting, were shown in Fig. 3. It can be observed that, in the initial experiment stage, an insignificant variation in the samples could be detected, as cracks appeared only on the edges of the samples and many bubbles formed in the water. With the increases in soaking time, the cracks propagated on the surface of the samples,
the sample began to disintegrated, and the disintegration products were mainly fine particles. After experiencing three drying-wetting cycles, obvious disintegration could be observed in the test and the main morphologies of the disintegration products were granular and massive. With the increases in the drying-wetting cycles, an intensified disintegration of the samples could be observed. In the meantime, the number of disintegrated products gradually increased, and the main disintegration product was granular. This result verifies that the red-bed argillaceous siltstone in this study shows a relatively strong disintegration characteristic. The disintegrated process of the red-bed argillaceous siltstone is gradual, and samples is crushed into small fragments, step by step. Water is the most direct influential factor on the disintegration of red-bed argillaceous siltstone, and drying exacerbates the disintegration.

3.2 Particle analysis of disintegration products

The evolution of the grain content with various particle sizes as the drying-wetting cycles increased is presented in Fig. 4.

In Fig. 4, it can be observed that the evolutions of particle content of the various particle sizes under the drying-wetting cycles share an inconsistent trend. To be specific, an insignificant variation in the content of particles that are larger than 5 mm could be detected in the initial stage of the experiment, followed by a rapid decrease as the experiment progressed. However, the rate of decrease in the later period gradually slowed down and stabilized, and the content of this particle size was approximately 2%. The evolution trend of the content of particles that are smaller than 0.25 mm is contrary to that of particles that are larger than 5 mm. It remained almost unchanged during the
first three drying–wetting cycles of the samples, which indicates the limited influence
of water on the samples at this stage. As the drying-wetting cycles increased to 10, the
content of the particles that were smaller than 0.25 mm increased gradually and reached
a remarkable value of 83.44%. Additionally, the evolutions of the content of the
particles that were 2-5, 0.5-2, and 0.25-0.5 mm in size shared a similar trend, in which
an insignificant variation could be recorded in the initial experiment process, followed
by an increase as the drying–cycles increased. However, the grain content gradually
decreased after reaching a maximum value until the end of the tenth drying–wetting
cycle. From these results, it can be concluded that the size of the samples is relatively
reduced during the disintegration experiment. Furthermore, the speed of the
disintegration of the small particles slowed down until disintegrating stopped. The
water-stability of the red-bed argillaceous siltstone increased when its particle size was
reduced to less than 2 mm.

3.3 Evaluation of durability

To evaluate the disintegration capacity of the red-bed argillaceous siltstone, and
quantify the amount of disintegration, the durability index, proposed by Franklin et al.
(1972) and recommended by the ASTM (2004) and the ISRM (2007), was adopted in
this paper. As describe by ASTM D4644-14 (2016) and Gamble (1971), the durability
index was widely used to evaluate the physical changes and durability of rocks during
drying-wetting cycles, and $I_{dn}$ is calculated as the percentage ratio of the final to the
initial dry sample weights as follows:

$$I_{dn} = \frac{m_n}{m_0} \times 100\%$$  (1)
In Eq. (1), $I_{dn}$ is the durability index after the $n$th cycle, $m_0$ is the initial dry weight of the sample, (g), and $m_n$ is the weight of the retained portion of the samples after the $n$th cycle, (g).

The values of the durability index $I_{d1-I_{d10}}$ obtained from different cycles, are plotted in Fig. 5. As can be observed, $I_{d1-I_{d10}}$ display a negative linear relationship with the number of cycles, and the values of the durability index gradually decrease with an increasing number of drying-wetting cycles. To describe durability index evolutions with the increasing number of drying-wetting cycles, a linear function is employed to fit the experimental data and the best fitting equation is obtained as follows:

$$I_{dn}=112.28-10.09n$$

(2)

The fitting result of the evolutions of the durability index with an increase in the number of drying-wetting cycles is illustrated in Fig. 5. The obtained exponential function fits well with the experimental data, and $R^2$ is 0.986. As the drying-wetting cycles increases, the durability index of the red-bed argillaceous siltstone decreases progressively. Specifically, the values of the durability index ($I_d$) slowly changed in the first and second cycles, notably decreased from the third cycle to the eighth cycle and varied insignificantly after the eighth cycle. Finally, when the number of drying-wetting cycles increased up to 10, the durability index reaches a minimum value of 11.57. Furthermore, according to the classification system from Franklin et al. (1972) and Zhu et al. (2019), the values of durability obtained in this study indicate that the durability of red-bed argillaceous siltstone is very low.

3.4 Microstructure characteristics
To monitor the evolution of the microstructure in the tested samples after exposing them to the drying-wetting cycles, SEM at 1000× magnification was used on samples after 0, 1, 3, 5, 7 and 10 cycles. The results are presented in Fig. 6.

Fig. 6(a) shows the initial microstructure characteristics of the tested sample. Before experiencing drying-wetting cycles, the sample had a dense structure, with few flaky aggregates and pores distributed on the surface. After experiencing one drying-wetting cycle, newly formed cracks could be occasionally observed, and the surface of tested sample became rough, as shown in Fig. 6(b). An increase in the drying-wetting cycles caused micro-crack propagation and typically a wider micro-crack distribution in the samples, as shown in Fig. 6(c). After experiencing three drying-wetting cycles, the number of pores and cracks gradually increased. Additionally, flaky aggregates appeared in the sample due to the softening of water. After fifth drying-wetting cycles, the cracks on the surface continued to develop, and the flaky aggregations were adsorbed on the surface with unevenly distributed pores, as shown in Fig. 6(d). After experiencing seven drying-wetting cycles, some clay minerals disaggregated, the flaky aggregations decreased with the appearance of fresh surfaces, as well as the surface began to be relatively smooth again, as shown in Fig. 6(e). Finally, when the number of drying-wetting cycles increased up to 10, as shown in Fig. 6(f), the clay mineral continuously dissolved, the flaky aggregations peel off, and the surface became smoother under the water-rock interaction.

As mentioned above, structures in the red-bed argillaceous siltstone, including pores and cracks, notable changed under cyclic drying-wetting conditions. It can be
observed in Fig. 6(a) that, the initial microstructure of the red-bed argillaceous siltstone had a dense structure, with few flaky aggregates and pores distributed on the surface. With the increasing number of drying-wetting cycles, the size and distribution of pores and cracks gradually increased, flaky aggregates appeared in the surface of tested sample due to the softening of water, and the sample became rougher than initial state, as shown in Figs. 6(b)-(d). During the process from the fifth to tenth drying-wetting cycles, the cracks continuously expand under interaction of the water-rock, flaky aggregations peel off and a fresh surface becomes exposed on the surface of sample, as shown in Figs. 6(e) and (f).

3.5 Evolution of ions concentration

Fig. 7 presents the evolution of cations concentration in the aqueous solution during the drying-wetting cycles. The concentration of cations in the solution significantly changed with the increase in the drying-wetting cycles. In the initial stage of the drying-wetting cycles, the concentrations of Na$^+$ and Ca$^{2+}$ showed notable increases, and the growth trend of Na$^+$ was higher than that of Ca$^{2+}$. When the number of drying-wetting cycles reached 3, the concentration of Na$^+$ reached its maximum value of 12.38mg/L, and then gradually decreased. The concentration of Ca$^{2+}$ reached its maximum value of 4.43mg/L after the seventh drying-wetting cycle and then remained unchanged until the end of the experiment. With an increase in the number of drying-wetting cycles, the concentration of K$^+$ and Mg$^{2+}$ also increased slightly, whereas the concentration of Al$^{3+}$ remained basically unchanged.

In addition, the evolution of anions concentration in the aqueous solution during
the process of drying-wetting cycles were presented in Fig. 8. As shown in Fig. 8, the concentration of anions in the solution changed significantly with an increase in the number of drying-wetting cycles. In which, the changes of $SO_4^{2-}$ and $SiO_3^{2-}$ being more obvious than those in $Cl^-$. In the initial stage of the drying-wetting cycle, the concentration of $SO_4^{2-}$ and $SiO_3^{2-}$ significantly increased and reached the maximum value in the third drying-wetting cycle. Subsequently, the concentration gradually decreased and became stable. Additionally, small amounts of $Cl^-$ were also detected in the aqueous solution, and the concentration remained almost unchanged during the entire drying-wetting cycle.

The results in Figs. 7 and 8 shows that the released concentrations of $Na^+$, $Ca^{2+}$, $SO_4^{2-}$ and $SiO_3^{2-}$ in the solution were higher than those of $Al^{3+}$, $K^+$, $Mg^{2+}$ and $Cl^-$, imply that the reaction ability of different minerals with water was different. Which is due to the fact that $Na^+$, $Ca^{2+}$, $SO_4^{2-}$ and $SiO_3^{2-}$ are active components in ion exchange and adsorption, whereas $Al^{3+}$, $K^+$, $Mg^{2+}$ and $Cl^-$ usually exist in stable compound states. For $Na^+$, $Ca^{2+}$, $SO_4^{2-}$ and $SiO_3^{2-}$ in the aqueous solution, it is mainly generated from the dissolution of calcite, albite, gypsum, montmorillonite and kaolinite, which causes a large amount of ions to enter into the soak solution, the chemical reactions are shown in Eqs. (3) to (7) (Zhou et al. 2004; Inglezakis, 2005; Xu et al. 2008). After the third drying-wetting cycles, the $Na^+$ and $SO_4^{2-}$ content decreases continuously, which may be caused by the ex-change adsorption of $Na^+$ and formation of $CaSO_4$, which can be expressed as Eqs. (8) and (9). In addition, $K^+$ and $Mg^{2+}$ is an important component of illite, illite has weaker hydrophilicity and ion-exchange adsorption capacity compared
with montmorillonite, and results in a very low content of K\(^+\) and Mg\(^{2+}\). The Al\(^{3+}\) and Cl\(^-\) are important components of insoluble minerals, usually in a relatively stable compound, therefore, the content of Al\(^{3+}\) and Cl\(^-\) in the soak solution is low with no obvious change.

\[ \text{CaSO}_4 \rightarrow \text{Ca}^{2+} + \text{SO}_4^{2-} \]  
\[ \text{CaCO}_3 + \text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- \]  
\[ 2\text{NaAlSi}_3\text{O}_8 + 11\text{H}_2\text{O} + 2\text{CO}_2 \rightarrow \text{Al}_2\text{Si}_2\text{O}_6(\text{OH})_4 + 2\text{Na}^+ + 2\text{HCO}_3^- + 4\text{H}_2\text{SiO}_4^{-} \]  
\[ \text{Na}_{0.33}\text{Al}_{2.33}\text{Si}_{1.67}\text{O}_{10}(\text{OH})_2 + 12\text{H}_2\text{O} \rightarrow 0.33\text{Na}^+ + 2.33\text{Al(OH)}_4^- + 4\text{H}_4\text{SiO}_4 + 2\text{H}^+ \]  
\[ \text{K}_{0.6}\text{Mg}_{0.25}\text{Al}_{2.3}\text{Si}_{3.5}\text{O}_{10}(\text{OH})_2 + 11.2\text{H}_2\text{O} \rightarrow 0.6\text{K}^+ + 0.25\text{Mg}^{2+} + 2.3\text{Al(OH)}_4^- + \text{H}_4\text{SiO}_4 + 1.2\text{H}^+ \]  
\[ \text{Na}^+(l) + \text{Ca}^{2+}(s) \rightarrow \text{Na}^+(s) + \text{Ca}^{2+}(l) \]  
\[ \text{Ca}^{2+} + \text{SO}_4^{2-} \rightarrow \text{CaSO}_4 \downarrow \]

4 Discussion

As mentioned previously, the intact samples gradually disintegrated, and the content of disintegration products with different particle sizes drastically changed, during the experimental process. With the increasing number of drying-wetting cycles, the size and distribution of cracks and pores in the microstructure of sample gradually increased, the surface of sample was no longer dense and uniform. Furthermore, according to the results obtained by XRD, presented in Fig. 1 and Table 2, the red-bed argillaceous siltstone analyzed in this study contains many soluble minerals and clay minerals, mainly include calcite, albite, gypsum, montmorillonite and kaolinite, which easily reacts with deionized water, then dissolves and disperses into the aqueous solution, as schematically shown in Fig. 9. Meantime, the expansion force generated from dissolution process is greater than the attraction between adjacent layers, which
exacerbates the disintegration of intact rock mass, as reported by Lin et al. (2005), Aja (2020), and Min et al. (2016). From these results, it is concluded that the disintegration of red-bed argillaceous siltstone in this study mainly be affected in two stages: water-absorption during wetting and dehydration shrinkage during drying.

During the wetting procedure, the water-absorption of red-bed argillaceous siltstone is mainly related to soluble minerals and clay minerals. When the red-bed argillaceous siltstone contacts with water, the water can interact with minerals through the pores and fissures. With the soluble minerals and clay minerals absorbing water, not only causes the dissolution of soluble minerals and the expansion of clay minerals, but also generates capillary forces which causes the internal cracks to further expand and disintegrate into small particles. Furthermore, after the disintegration caused by the water-absorption, the structure of samples become weakens and softens. During the drying process, the increases in temperature accelerate the previously wetted samples lose water, which further destroy the structure of samples, and increase the rate of disintegration. With the increasing number of drying-wetting cycles, the sample continuously absorb water and lose water, which aggravates the losses of minerals, increases the surface pores and cracks of the sample, and makes the sample gradually disintegrate. Thus, the disintegration of red-bed argillaceous siltstone is the result of the synergistic effect of water and temperature, under drying-wetting cyclic conditions. In the stage of water absorption, the dissolution of minerals and the change of microstructure destroy the stability of the sample structure, which promotes the disintegration of the sample. In the stage of water loss, the increases in temperature and
the dehydration shrinkage of sample accelerate the disintegration of red bed argillaceous siltstone.

5 Conclusions

To better understand the disintegration behavior of red bed soft rock, the disintegration characteristics, durability, microstructural characteristics and ions concentration evolution of red-bed argillaceous siltstone under drying-wetting cyclic conditions were investigated in this study. The main conclusions are as follows:

(1) The disintegration process of this red-bed argillaceous siltstone during the wetting cycle is gradual, the samples is gradually crushed, and large particles gradually transform into small particles. The drying process exacerbates disintegration. The particle content of disintegration products with different particle sizes significantly changed during the process of drying-wetting cycles.

(2) The durability index ($I_d$) of the red-bed argillaceous siltstone displays a negative linear relationship with the number of cycles, and after experiencing tenth drying-wetting cycles, the values of the durability index reaches a minimum value of 11.57, it means that the durability of red-bed argillaceous siltstone is very low.

(3) In the microstructural analysis, a continuous drying-wetting process results in significant variation in the surface structure of the sample. The sample surface become disordered and complicated, some pores are gradually penetrate or merge into the large pores, and new micro-fractures are generated.

(4) The interaction between water and calcite, albite, gypsum, montmorillonite and kaolinite is the most important factor that influences red-bed argillaceous siltstone
disintegration. A notable change in concentrations of ions in the aqueous solutions during disintegration suggested that continuous dissolution of minerals results in a large amount of mineral loss under the action of cyclic drying-wetting.

(5) Based on the results obtained from experiments, the disintegration of red-bed argillaceous siltstone is the result of the synergistic effect of water and temperature. The dissolution of minerals and the change of microstructure during wetting destroy the stability of the sample structure, which promotes the disintegration of the sample. The increases in temperature and the dehydration shrinkage of sample during drying accelerate the disintegration of red bed argillaceous siltstone.

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Declaration of competing interest

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.

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Evolutions of durability Index (Id) with number of drying-wetting cycles.

\[ I_{dn} = 112.28 - 10.09n \]

\[ R^2 = 0.986 \]
Figure 6

Microstructure characteristics of the tested sample subjected to (a) initial state and after (b) 1 cycles, (c) 3 cycles, (d) 5 cycles, (e) 7 cycles, and (f) 10 cycles of drying-wetting.
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