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Molding simulation of soft rock based on natural red bed materials

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Abstract: Rock simulation is the core of the researches such as geotechnical engineering model test and geological core simulation tests. At present, however, the molding simulation results based on artificial materials are greatly different with that from the actual rock properties due to the limitations of existing similarity theory and technical approaches, especially for the molding simulation of soft rock. In this study, the natural red bed is taken as the raw materials and the traditional diagenesis simulation system is improved. The influences of temperature, pore fluid pressure and overlying pressure are considered herein. The formation process of red bed is realized from the loose rock and soil particles to the rock and the engineering standard size soft rock cores are obtained. Based on the comparison results of diagenesis process, physical properties, chemical properties and mechanical properties between the natural red bed soft rock and the soft rock core that based on natural red bed materials, it is found that the simulated soft rock cores have similar properties with that of the natural red beds soft rock. This study break through the limitations where only certain properties can be generally satisfied from the artificial material similarity simulation, 3D printing or other methods. This study can provide a new manufacturing ideas and methods for the research of large demand soft rock core with differing functional requirements.

Keywords: natural red beds material; soft rock; molding simulation; standard size rock core; diagenesis process

1 Introduction

Rock simulation is the core of the research fields such as geotechnical engineering tests and geological core simulation tests, especially for the molding simulation of soft rock, which is one of the frontier research topics that need to explore at present. Red bed soft rock is a typical damage-prone rock mass in red bed and the red bed soft rock exists widely in red bed engineering and geology[1]. Some red bed soft rock mass is difficult to obtain due to the deep burial depth, however, it will be inevitably encountered in the development of deep ground. Because of the high cost of obtaining the natural rock core, it is hard to meet the requirement of a large quantity of researches. In this consideration, it is significant to simulate soft rock of red bed. Deformation and failure of the red bed often lead to disasters such as landslide, uneven settlements and collapses[2–4], which are closely related to the physical, mechanical and chemical properties of red bed rock mass[5]. The traditional similarity tests only select certain properties for the molding simulation, which is hard to reflect the actual deformation and failure process. By improving the similarity of the simulation results among the multiple properties such as physical, mechanical and chemical behavior of the red bed rock mass, it is therefore to consider that molding simulation tests of red bed engineering is one of the crucial approaches to reveal the catastrophe mechanism. One of the effective way to ensure the test similarity is to model the rock formation process in more details. It is worth to mention that the difficult and the key in this similarity test is the molding simulation of the red bed soft rock.

There are two important tasks in the molding simulation of red bed soft work: the model tests and the artificial cores. The red bed model tests mainly involved two methods based on the different test materials, 1) the natural red bed material and 2) the artificial material. For the model tests that based on the natural red bed material, the model density is normally achieved using compaction method[6]. It has been widely studied for the red bed slop model[7]. In addition, model tests also included the researches of the creep and disintegration behavior[8]. However, most of the mentioned studies are only focused on the similarity of density and similarities of cementation degree and mechanical property are hard to guarantee. For similar model tests based on the similar materials, the material selection should be based on the similarity relationship and normally only consider similarities in physical or mechanical parameters. In general, the similar materials include the skeleton particles and the cementitious materials. The most used materials for the skeleton particles are

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barite powder, quartz sand, talc powder, iron sand, barium powder, etc[9]. The cementitious materials are usually the quicklime and gypsum[10]. When compared the chemical composition of the natural red bed rock mass, it is hard to keep consistent of chemical composition within the similar materials. However, the chemical properties play a key role in the failure mechanism for the red bed soft rock. At present, there are few studies on the artificial soft rock cores of red bed and the core fabrication is basically performed only according to certain aspects of rock physics and mechanical properties[11]. In terms of physical properties, the density, pore structure and porosity are the main considering aspects[12]. In terms of mechanical properties, the uniaxial compression strength and permeability are the main parameters[13]. The selection of artificial core materials mainly includes skeleton particles, clay minerals and cementing agents. The skeleton particles are mainly river sand and quartz sand. The clay minerals are based on the specific minerals of the simulated rock masses. Cemented core and loosen core are the two main types[11]. On one hand, for the cemented core, the cementing agents have two types: the organic and inorganic agents. The widely used cementing agents are the epoxy resin and the aluminum phosphate in the organic and inorganic cementing agents, respectively. Beside, cement is also widely used as the binder agent[14–15]. For the loosen core, on the other hand, it is mainly filled with steel quartz tube, sometimes with a small amount of cement. In general, the cemented core has a relatively high UCS value when compared that with the loosen core, but there are large chemical property variations between the natural red bed material and the cemented core due to the addition of cementing agent and the selection of non-natural raw materials. Further, it is difficult to match the physical and mechanical parameters between the loosen core and the natural red bed materials. In recent years, 3D printing technology has been applied to preparation of artificial cores. The materials that used in 3D printing are not from the natural rock masses[16] and the 3D printing mainly focuses on the simulation of physical structure forms. The simulation of chemical and mechanical properties is still on the initial exploration stage. In addition, traditional artificial core facilities require manual control and can only be heated and pressurized. Some high automated diagenesis system is also existed in nowadays. However, the core diameter of the traditional diagenesis system is normally 25 mm, which is hard to meet engineering scale requirements.

For the purpose of solving the above issues, this study develops and improves the traditional diagenesis system to meet the standard size core preparation for geotechnics engineering. Based on the improved diagenesis system, the molding simulation of soft rock is conducted based on the natural red bed raw material by considering the influence of temperature, pressure and pore pressure on the rock core formation process. Through the comparison results of diagenesis process, physical, chemical and mechanical properties between the natural red bed soft rock and the soft rock core that based on natural red bed materials, the rationality and reliability of soft rock molding simulation are proved based on the natural red bed materials. This study solves the problem of only meeting certain aspects of the natural properties in the tradition simulation tests such as the limited artificial material preparation and 3D printing. This study could lay the foundation for future development of soft rock molding equipment with larger scale and variable simulation shapes.

2 Research content

2.1 Test purpose

The purpose of the test is to utilize the nature red bed material and diagenesis simulation approach for producing artificial soft rock cores that have similar properties in term of the chemical, physical and mechanical properties of natural red bed soft rocks. In addition, the test is aimed to improve the shortcomings in the traditional similar materials of artificial core and further lay the foundation for development of more advanced soft rock molding equipment.

2.2 Test principle

The red bed rock belongs to terrigenous clastic sedimentary rock of the sedimentary rock. The diagenesis process of red bed rock conforms the diagenesis phase division of the clastic rock. The sedimentary rock subjects to a combination effect of the overburden pressure, temperature and pore fluid pressure during the diagenesis process. In this study, the actual diagenesis condition during the entire diagenesis process are restored as much as possible based on the natural red bed materials. The ultimate goal of this test is to ensure the property similarity between the artificial rock core and the natural red bed soft rock.

2.3 Improvement of test equipment

The core diameter of the conventional diagenesis system is normally 25 mm, which does not meet the standard specimen dimension used in the project. In this consideration, the diagenesis system is improved in this study (as shown in Fig.1). This developed system has the capacity to apply the temperature, overburden pressure and pore fluid pressure at the same time during the test. The improved equipment can simulate the diagenetic process and in-situ state at conditions up to a maximum depth of 8 000 m.

In order to adapt the core diameter requirement of geotechnical engineering standard, the diameter of the sample loading bucket is enlarged to 50 mm, as can be seen from

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Fig.1(b). Due to the size changing of the loading bucket, the diameters of the reactor, the overlying pressure rod and the mold release pressure rod are also changed correspondingly. Once the specimen size is enlarged, the heating performance of the device needs to be improved at the same time to ensure the temperature in the core center can reach to the pre-set value in a short time. It is hence to use a precision furnace for the heating furnace, which is connected directly to the reactor. In this fashion, the system can heat up the core to the pre-set temperature quickly. The main parameters of the system are as follows:

(1) Specimen size: diameter 50 mm with a maximum height of 160 mm.

(2) Loading: simulated overburden pressure: 0–200 MPa with a precision of ±0.2 MPa; Temperature: room temperature –500℃ with a precision of ±1℃; pore fluid pressure 0–100 MPa with a precision of ±0.2 MPa.

(3) The data is collected automatically by the test system and the collection is controlled intelligently in stages during the test.

(a) Photo of the improved diagenesis system

(b) Rock core mold and sealing device

Fig.1 Rock core diagenesis system

2.4 Test plan

The test is mainly divided into four stages: raw material selection, weighing and mixing, diagenesis simulation, and de-molding and drying. This study simulates the argillaceous siltstone in the red bed soft rock mass. The porosity of natural core ranges from 4%–17%. According to the previous back analysis researches of porosity[17], the historical burial depth is estimated in the range of 4 000–5 000 m and it is then lifted to the near surface due to the geological actions. In this consideration, the simulated depth is assumed as 5 000 m.

In the raw material selection stage, the natural red bed argillaceous siltstone is selected as raw material, which is crushed, ground, and sieved. The grain size distribution is configured based on the standard of natural red bed of argillaceous siltstone and details are shown in Tab.1. In this study, the cements of selected natural red bed soft rock are mainly argillaceous cement and iron cement, which also contain a small amount of calcium and siliceous cement. Because of the existence of relatively high clay minerals, the cementation structure is a matrix cementation. To achieve the strength of the natural red bed, the sodium silicate with a modulus of 3 is chosen as the cementing agent. The sodium dihydrogen phosphate is selected as the curing agent because the sodium silicate will decompose into SiO_2 and CO_2 under the heating condition and SiO_2 is an internal component contained in the natural red bed. Based on the previous studies[18], the ratio of curing agent to cement is set to 2%.

Table 1 Grain size ratio of natural red beds argillaceous siltstone

Grain size/ mm	1–2	0.5–1	0.25–0.5	0.0625–0.25	<0.0625
Content/ %	4	12	7	17	60

In the weighing and mixing stage, according to the parameters in Tab.1, each grain size of natural red bed powder is weighed corresponding to the mass and then mixed uniformly. The total mass of the raw materials in one test is 800 g, the cement and curing agent mass is 140 g and 3 g, respectively. In addition, 60 g water is added. The above-mentioned materials are mixed until reach to a uniform dispersion state. In general, it needs 20 min to ensure all the grains are all wet and do not form agglomerates.

According to *the Division of Diagenetic Stages in Clastic Rocks* (SY/T 5477－2003)[19], in the diagenesis simulation stage, the diagenetic process of red bed soft rock is simulated in stages with considering the effect of overburden pressure, pore pressure (pore water is assumed as tap water), and temperature. The simulation stages are considered from the early diagenesis stage to the late diagenesis stage and the specific diagenesis parameters are shown in Tab.2. The mixed materials need to be pre-pressed within a sample cylinder under 20 MPa pre-pressure before putting the mixed materials into the reactor. The depth is calculated based on the ground temperature gradient of 30 °C /km and the surface temperature is assumed as 20 °C. The pore water is calculated based on the hydrostatic pressure with g = 9.8 m/s^2. The constant pressure mode of diagenetic system is used during the applying of pore water pressure. The water is injected through the thin tube at left end (red oval) in Fig.1(b) and the injected water pressure is set based on the values at different stages in Tab.2. The pre-set pressure will be automatically applied and maintained by the diagenetic system and the real-time pore water pressure value can be displayed on the control screen. The average bulk density of the strata is assumed as 25 kN/m^3. The simulation time is determined to be 20 h after many preliminary tests. Different pressurized time intervals are checked such as 8, 14, 20, 26, 32, and 38 h and it is found that a close similarity of the core density and UCS can be ensured between the core and the natural red bed under 20 h pressurized time.

Table 2 Parameters of diagenesis stage

Stages	Temperature / ℃	Modelling depth / m	Pore pressure / MPa	Overburden pressure / MPa	Modelling time / h
1	50	1 000	9.80	25	2
2	70	1 670	16.37	42	2
3	100	2 670	26.17	67	2
4	150	4 300	42.18	108	2
5	170	5 000	49.00	125	12

In the de-molding and drying stage, the core cooled down to the room temperature is taken out from the sample preparation device using the de-molding device. It should be noted that the pressure loading rate needs to be controlled carefully and the core should be taken out slowly and evenly during the taking out procedure to prevent from being damaged by human. The core is then dried and stored in plastic wrap after the core is taken out.

3 Test results and discussion

In total, eight soft rock cores are made and numbered as A-1 to A-8. In addition, three natural red bed rock cores are prepared and numbered as N-1 to N-3. Figure 2 shows the photos of rock cores from human-made and natural red beds. Both the prepared specimens are matrix cemented. To discuss the similarity between two types of specimen, the testing and processing of the rock properties are conducted, which are concerned by the rock engineering projects:

(1) Diagenesis process: include the variation law between the compressive extent and time.

(2) Chemical properties: include measurement of mineral composition by using X-ray powder diffractometer (XRD), element measurement using X-ray energy spectrometer (EDS) and backscattered electron diffraction analyzer (EBSD), measurement of pH value and ion concentration changes of the solution after the soaking test.

(3) Physical properties: include measurement of size, mass, porosity, and microstructure of electron microscope and disintegration discussion.

(4) Mechanical properties: include the uniaxial compression test (UCS) and triaxial compression test (TCS) and then the UCS, elastic modulus, cohesion, and internal friction angle are obtained.

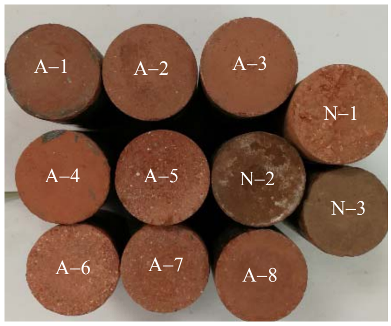


Fig.2 Comparison of natural red beds and artificial cores

3.1 Diagenesis process

During the diagenesis process of the artificial specimen preparation, the real-time change data of the compressive volume is recorded. Figure 3 shows the relation between the amount of compression and time for the artificial soft rock core A-1 to A-8. It is seen that a rapid increasing of compression volume is observed at the initial stage and the compression rate tends to be slow as the diagenetic stage continues, which reaches to a stable stage after 10 h. In the sedimentation process, the porosity of sedimentary rocks will change more and more slowly. The porosity is around 40%–50% at the initial stage of the deposition and the porosity will drop to about 5%–15% under the burial depth below 4 000 m[17]. The compression ratio is about 36.8%–47.4%. For the convenience of loading materials, the artificial core is pre-compressed under 20 MPa, which is equivalent to an initial burial depth of 800 m. The compression ratio is therefore requiring a correction for the natural red bed materials. That is to say 28%–38% porosity at the initial compression stage is equivalent to 15.3%–34.7% porosity after the correction. The simulated depth of the artificial red bed core is 5 000 m and the height is roughly 125 mm at the beginning of compression. From Fig.3, it is found that the amount of compression is about 19.52–31.89 mm with a compression ratio of 15.62%–24.89%. The compression ratio of artificial rock core in this study lies in the range of compression ratio that from the back analysis based on the porosity of the natural red bed soft rocks[17]. It is therefore safe to consider the compression ratio for both rock cores are similar.

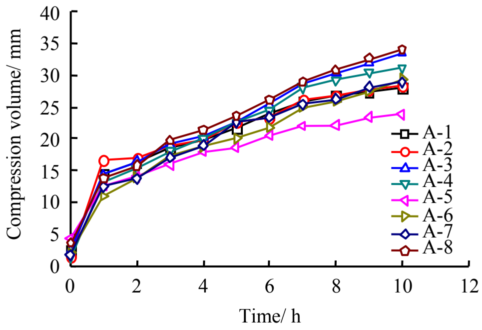


Fig.3 Compression volume changes during diagenesis of artificial core

3.2 Chemical properties

Elemental and mineral tests are performed for the soft rock core to verify the similarity of minerals and elements before and after the tests. In terms of soft rock, the chemical properties are also extremely important when contact with water. In this fashion, the changes of the ion concentration and pH value of the solution are also measured after soaking in water.

Table 3 shows the chemical element content of artificial soft rock cores and the natural red bed cores using the EDS and EBSD analyzers. Each specimen is measured three times and take the mean value. It is seen that element content of natural red bed core N-1 is very close to that of artificial rock core A-1 such as the elements of Si, Al, Ca, O, which account for more than 85% of the total content. Beside, it is shown that the content difference of the two cores is within 8%. However, it is also seen that there is a larger variation of the element content among the four elements of Na, K, Mg, and C. The main two reasons are: 1) the measurement is very difficult due to the low element content with a relatively large quantitative analysis error; and 2) very small amount and discrete of powder is used to determine the content. However, from the overall analysis, the chemical element types of artificial core have not changed. Further, the element content difference of Si, Al, Ca, and O (account for more than 85% of the element) is within 8% between the natural red bed core and the artificial rock core. Based on the above analysis, it is hence considered that there is a high similarity of chemical element composition between the natural red bed core and the artificial rock core.

Table 3 Chemical element content of artificial core and natural red beds (unit: %)

Core number	Si	Al	Fe	Ca	Mg	Na	K	H	C	O
A-1	24.69	7.32	4.54	4.41	1.23	2.54	3.04	0.00	0.00	52.23
N-1	26.79	7.32	6.42	4.24	0.15	0.94	1.32	0.00	1.10	51.37

The XRD mineral quantitative results of artificial soft rock core A-1 and nature red bed rock core N-1 are presented in Tab.4. It is seen from Tab.4 that no metamorphic mineral is produced in the artificial red bed debris specimens, which indicates that the pre-set temperature and pressure conditions are reasonable and acceptable. The mineral content of core A-1 is similar to that of the natural red bed core N-1. The deviations of most of the mineral content are within 20% except for the calcite and hematite, which associates with relatively large differences. The large differences of mineral content may be mainly result from the micro-area measurement of XRD. Dispersion occurs for different specimens and large content deviation is expected in the XRD quantitative analysis. In sum, it is considered that the mineral groups are consistent between the natural red bed core and the artificial red bed core that based on the nature red bed materials. The difference between the two cores lies in the range that from 8.96% to 32.7% due to the influence of quantitative analysis and measurement error.

Table 4 Mineral content of artificial core and natural red beds

Core number	Quartz	Feldspar	Mica	Calcite	Kaolinite	Illite	Montmorillonite	Hematite
A-1	41.64	4.28	6.17	9.20	18.28	6.69	7.63	6.11
N-1	37.91	3.75	5.03	13.67	20.15	8.28	6.61	4.60

In the soaking test of soft rock cores, two natural red bed soft rock blocks are selected and numbered as N-S1 and N-S2. Two complete rock blocks are also chosen from the crushed artificial cores of A-2 and A-3 and the two artificial rock blocks are numbered as A-2S1 and A-3S1 in order conduct a comparison between two types of rock cores. The mass prior to the soaking are 297.35, 247.60, 207.65, and 218.30 g for the N-S1, N-S2, A-2S1, and A-3S1, respectively. The mass ratio is 1:0.83:0.70:0.74. Beaker is used to add tap water for soaking purpose and the final solution volume is 1 000 mL. The pH value and ion concentration are measured every 30 min for the four group solutions. The pH value and ion concentration of the solution are shown in Fig.4 and Fig.5, respectively. It is seen that the solution pH values of the four group specimens increase as the time increases and eventually shows alkaline. There is a rapid increasing period of pH value between 0 and 60 min and the pH value tends to be stable after 60 min. According to the variation trend of pH value in the solution after soaking in water, a consistent change trend is observed between the artificial rock core and the natural red bed rock core. The pH value of the solution is in the range of 8.25–8.45 after 180 min.

In terms of the concentration change of solution icons, the trends of the four group samples are the same. It is observed a rapid-increasing trend in the time of 0–30 min and a fast-increasing trend in the time of 30–60 min and a stable and slightly-increasing trend with small fluctuations for concentration of solution ions after 60 min. When the time is 180 min, for instance, the concentration ratio of Ca^{2+} is N-S1: N-S2: A-2S1: A-3S1 = 1: 0.89: 0.74:0.75, which is similar to the mass ratio of 1.0: 0.83: 0.70: 0.74. This observations indicate that ratio of the concentration change magnitude is 1:1.07:1.06:1.01 without the consideration of influence of the original mass. In addition, the analysis results of other ions are similar to the results of Ca^{2+} and with similar change trends. In general and to sum up, the ionic concentration of the artificial red bed soft rock cores increases after soaking within tap water and the results show a similar increasing trend and increasing magnitude for the ionic concentration.

3.3 Physical properties

The artificial soft rock cores of A-1 to A-8 are de-molded and dried and the diameter of all cores are unchangeable and should be 50 mm. The rock core of the natural red bed is extracted using a coring machine and the cores are ground and dried. The basic physical parameters of all cores are measured and shown in Tab.5. The dry density of artificial soft rock is in the range of 2.0–2.39 g/cm^3. While the density of the natural red layer is in the range of 2.13–2.47 g/cm^3. The mean dry density of artificial core is about 4.8% lower than that of the natural red bed cores and the minimal density value of artificial core is smaller than that from the natural red bed rock cores. However, most of artificial core densities are still in the range of dry density for the natural red bed rock. A better consistency of dry density is observed between the artificial core and the natural red bed core. In addition, the porosity of artificial soft rock cores is in the range of 8%–22% and the porosity of natural red bed cores is in the range of 4%–17%. The maximum porosity value of artificial cores is larger than that from natural red bed rock cores. However, most of the porosity values of the artificial cores are in the range of porosity values of natural red bed cores. Hence, a good porosity consistence is also observed between the artificial cores and the natural red bed cores.

The hydration of clay minerals is a widespread phenomenon, which plays an import role in the soft rock engineering. In our tests, a small amount of water is added in the weighing and mixing stage and a 9.8 MPa overburden pressure is then applied within 30 min after the water is added. Previous studies has been revealed that the mudstone cores with a clay mineral content that up to 46.8% hardly swell within 30 min after adding water. In addition, the expansion could be suppressed under applying pressure[20]. It is hence safe to consider that the crystal layer structures of clay minerals are not changed largely before and after test. Figure 6 presents the scanning electron

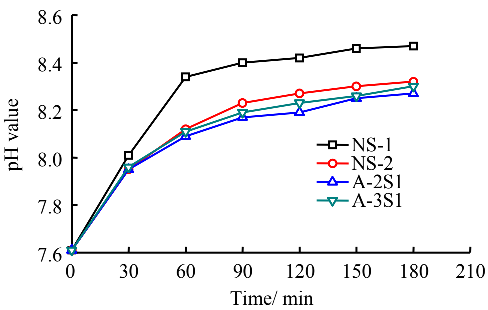


Fig.4 pH changes of artificial core and natural red beds

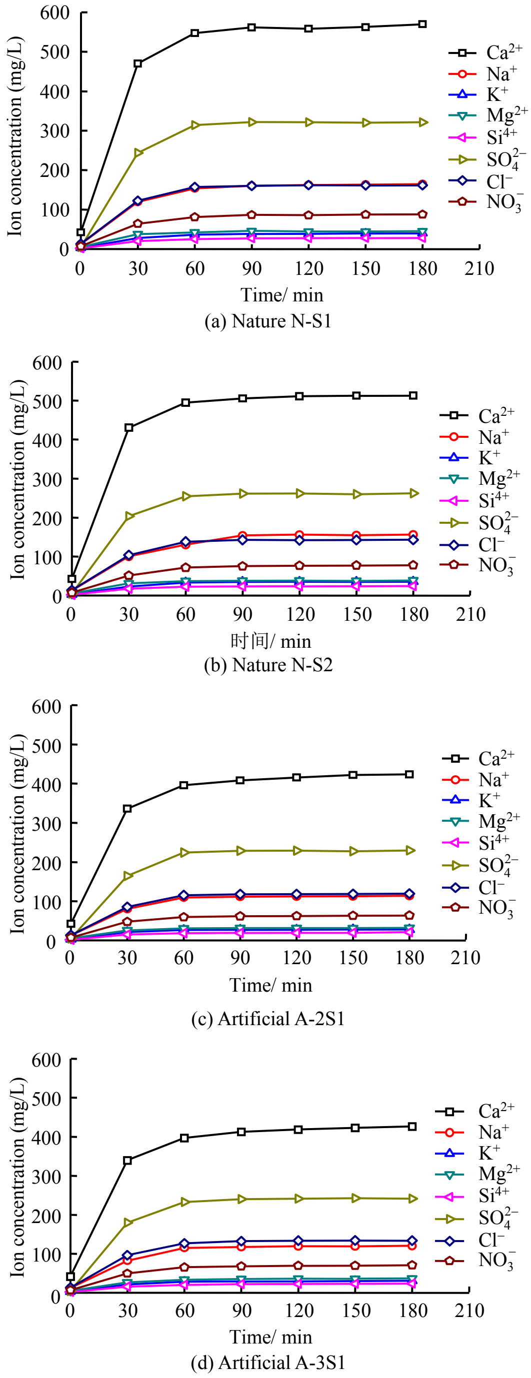
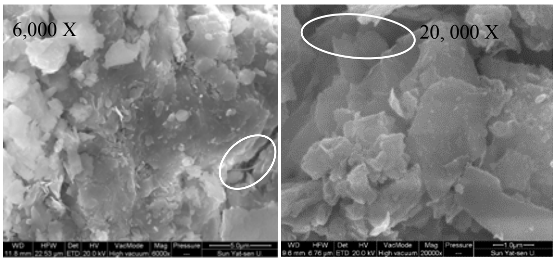


Fig.5 Ion concentration changes of artificial core and natural red beds

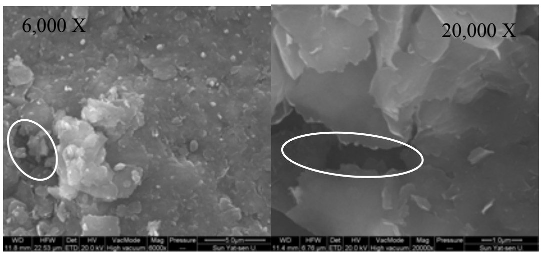
Table 5 Basic physical parameters of artificial core and natural red beds

Rock core number	Mass / g	Height / mm	Volume / cm^3	Dry density / (g/cm^3)	Porosity / %
A-1	398.20	101.44	199.08	2.00	22
A-2	393.80	86.88	170.50	2.31	10
A-3	392.20	96.04	188.48	2.08	19
A-4	412.00	101.16	198.53	2.08	19
A-5	413.30	88.04	172.78	2.39	7
A-6	462.50	100.05	196.35	2.36	8
A-7	441.20	105.76	207.55	2.13	17
A-8	384.60	84.21	165.26	2.33	9
N-1	420.60	100.69	197.60	2.13	17
N-2	397.85	87.92	172.54	2.31	10
N-3	455.75	93.96	184.40	2.47	4

microscope images of the microstructure for the artificial red bed core and the natural red bed. It can be found from the 6 000 times figure that both the cores are mainly formed by sheet-like structures, but the natural red bed core shows a slightly denser structure. The flaky structures are observed for both the two cores under the 20 000 times zoom-in picture. In addition, both of two cores have small fractures with same form, which are marked by ellipses. The flaky structure is related to the mineral types, which contains flaky structure such as clay minerals and mica. From the microstructure point of view, it is again to conclude that the artificial red bed soft rock cores are similar to the natural red bed rock cores.



(a) Artificial red bed argillaceous siltstone



(b) Natural red bed argillaceous siltstone

Fig.6 Scanning electron micrograph of artificial core and natural red beds

3.4 Mechanical properties

The uniaxial compressive strength is first measured for both the artificial red bed soft rocks and the natural red bed soft rocks under the dry state and the uniaxial stress–strain curves of the two groups are obtained and shown in Fig.7. The ultimate UCS values are as follows: the UCS values for the artificial red bed soft rocks are in the range of 9.30–9.83 MPa with an average value of 9.49 MPa. The UCS values of natural red bed soft rocks are in the range of 9.25–11.73 MPa with an average value of 10.29 MPa. The UCS value of the natural red bed soft rock is slightly higher (about 7.8%) than that from the artificial red bed soft rocks (7.8% is calculated as ratio of the difference between the average UCS value of the natural red bed soft rock and the artificial red bed soft rock to the mean UCS of natural red bed soft rock, similarly hereinafter), but both two types of rock core are belonged to the soft rock category (5 MPa $\leqslant R_c \leqslant$ 15 MPa). In addition, based on the trends of the stress-strain curve, a similar trend is observed for the stress-strain relations. It can be calculated from the stress-strain curves that the elastic modulus for the artificial red bed soft rock is from 258 MPa to 320 MPa with an average value of 282 MPa; the elastic modulus for the natural red bed soft rock is from 267 MPa to 412 MPa with an average value of 338 MPa. The Young's modulus of the two rock cores are similar to each other while the natural red bed has a slightly higher value than that of the artificial red bed soft rock (about 16.6%). The test modulus are also lied in the range of the elastic modulus of natural red muddy siltstone such as from 115.7 MPa to 518.5 MPa[21]. In this consideration, the red bed soft rock produced in this study meets the mechanical properties of the UCS and the elastic modulus of natural red bed soft rocks.

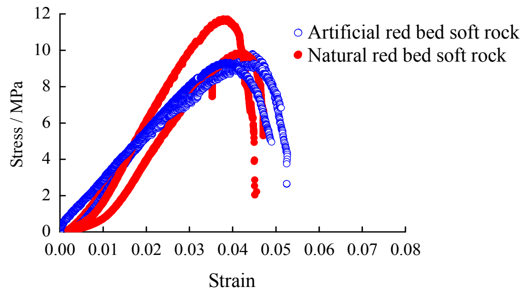


Fig.7 Uniaxial stress–strain curves of artificial core and natural red beds

The triaxial compression tests include the artificial soft rock cores A-4, A-5, A-6, A-7, A-8 and the natural red bed rock cores N-2 and N-3. The Mohr stress circle and strength envelope are plotted based on the triaxial compression tests (Fig.8). From Fig.8, the cohesion and internal friction angle of the artificial red layer soft rock are calculated as 1.62 MPa and 33.02°, respectively. The cohesion and friction angle for the natural red bed rock are 1.85 MPa and 35.75°, respectively. Compared with the artificial red bed rocks, the cohesion and friction angle of natural red bed are 12.4% and 7.6% higher, respectively. The triaxial strength of the natural red layer is slightly higher than that of the artificial red rocks, which may be related to 1) the discreteness of sample preparation, 2) the abrupt changes of the diagenetic pressure and temperature during the simulation process, and 3) the influence of the triaxial confining pressure, which needs further study. According to previous studies on natural red beds[21], it is shown that the triaxial strength properties of both two types of rock cores are within the reasonable range of the natural red beds. The triaxial compression behavior and related strength parameters of the artificial red beds are relatively close to that of the natural red beds. In other words, the artificial soft rock cores can meet the test needs.

For the mechanical properties of the two rock cores, the disintegration effects are also performed in this study. The disintegration effect is observed visually in stages during the water-bubble tests. Figure 9 compares the disintegration effects at 10 min, 30 min, and 24 h. It is seen that a similar disintegration effect is observed between the artificial red bed soft rock and the natural red bed soft rock. The same disintegration time is the main manifestation for the two rock cores. The shapes of the rock block can be clearly seen at 10 min and the shape are blurred at 30 min, which indicates a server disintegration at this stage. After a completed disintegration within 24 h, the nature of disintegration can be seen then. The natural N-S1, N-S2 specimens are disintegrated in smaller pieces, but the artificial A-2S1 and A-3S1 specimens are disintegrate into various debris, which is mainly consist of fine particles and the solution is darker in color. In general, although the artificial soft rock core and the natural red layer have certain differences in the disintegration forms, the disintegration time of the two rock cores is close to each other.

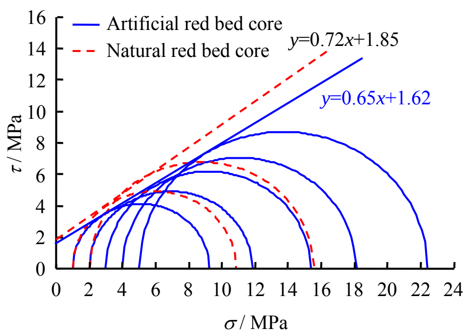
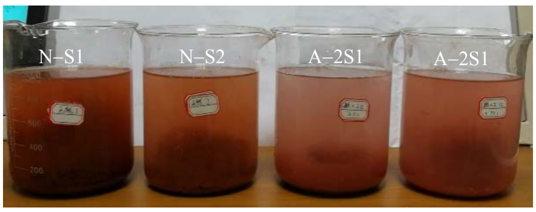
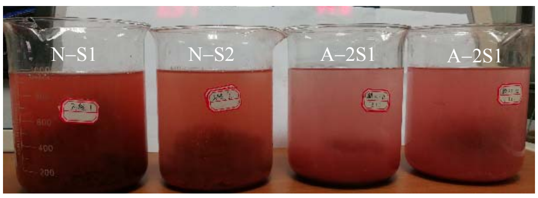


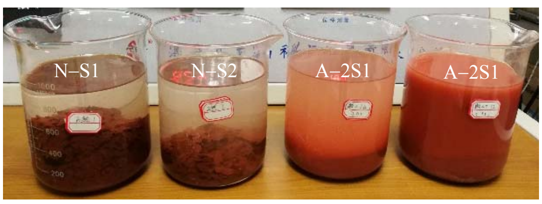
Fig.8 Triaxial Mohr strength envelope of artificial core and nature red beds



(a) 10 min disintegration effect



(b) 30 min disintegration effect



(c) 24 h disintegration effect

Fig.9 Disintegration comparison

This study compares the properties of artificial red bed soft rock and natural red bed soft rock in terms of aspects of diagenesis process, chemistry, physics and mechanics. When comes to the reliability of the performance comparison between artificial core and the natural core during the tests, different parameter values are required for different test requirements. Taking the soft rock similarity model test as an example, based on many previous researches on the soft rock similarity tests [9–10], a good modelling effect is expected when the mechanical parameters have following difference: 25% at density difference, 30% at internal friction angle difference, and 35% at cohesion difference, 30% at elastic modulus difference, and 15% at the UCS difference. The red bed soft rock cores are not based on similar materials in this study. The prepared rock cores of this study not only meet the basic parameters requirements, but also ensure the similarity to other physical, mechanical, and chemical parameters, which accord with the test requirements of soft rock engineering.

4 Conclusions

(1) This study develops and improves the traditional diagenesis system to meet the standard size core preparation for geotechnics engineering. Based on the improved diagenesis system, the molding simulation of soft rock is conducted based on the natural red bed raw material by considering the influence of temperature, pressure and pore pressure on the rock core formation process. The molding results have high degree of similarity when compared that with the natural red bed rocks. This study can provide some new manufacturing ideas and methods for the research of soft rock masses.

(2) During the diagenesis process，the artificial rock core has a compression ratio of 15.62–24.89% and the compression ratio of the natural red bed rock is in the range of 15.3%–34.7% based on the back analysis of the porosity. The compression ratio of artificial rock core in this study lies in the range of compression ratio that from the back analysis based on the porosity of the natural red bed soft rocks. Further, the diagenesis processes are similar for both rock cores.

(3) The scanning electron microscopy results showed that both the artificial soft rock core and the natural red bed core show a sheet-like structures and both cores contain micro-cracks. In terms of chemical properties, the two types of rock cores have comparable contents of the quartz, feldspar, mica, kaolinite, hematite, and clay minerals. Besides, the element content difference of Si, Al, Ca, and O (account for more than 85% of the element) is within 8% between the natural red bed core and the artificial rock core. After the two type rock cores are soaking in water, there is a rapid increasing period of pH value between 0 and 60 min and the pH value tends to increase slowly after 60 min and tends to be stable after 180 min with the pH value in the range of 8.25–8.45. For the ion concentration in the two solutions, the two type rock cores have similar increasing trend and with similar values. In terms of physical properties, the dry density and the porosity of

artificial soft rock are in the range of 2.0–2.39 g/cm^3 and in the range of 8%–22%, respectively. While for the natural red bed rock cores, the density and the porosity density are in the range of 2.13–2.47 g/cm^3 and 4%–17%. All the above factors are within a reasonable range and are relatively close to each other. Furthermore, the disintegration speeds for the two cores are similar. Both cores have server disintegration within 30 min and a completed disintegration occurs within 24 h. Therefore, there are good similarities between the produced artificial soft rock and the natural red bed soft rock based on the comparisons among the micro-structure, chemical properties, and physical properties.

(4) In terms of mechanical properties, the UCS values for the artificial red bed soft rocks are in the range of 9.30–9.83 MPa with an average value of 9.49 MPa. The elastic modulus for the artificial red bed soft rock is from 258 MPa to 320 MPa with an average value of 282 MPa; The UCS values of natural red bed soft rocks are in the range of 9.25–11.73 MPa with an average value of 10.29 MPa (about 7.8% higher). The elastic modulus for the natural red bed soft rock is from 267 MPa to 412 MPa with an average value of 338 MPa (about 16.6% higher). The cohesion and internal friction angle of the artificial red layer soft rock are 1.62 MPa and 33.02°, respectively. The cohesion and friction angle for the natural red bed rock are 1.85 MPa and 35.75° (about 7.6% higher), respectively. The difference in mechanical parameters of the two type rock cores is small, but the natural red bed core is slightly higher parameters, which indicates that the artificial soft rock cores and natural red bed cores are similar in the mechanical properties in this study.

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