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Shear strength features of soils developed from purple clay rock and containing less than two-millimeter rock fragments

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Abstract: Soil shear strength is an important indicator of engineering design and an essential parameter of soil precision tillage and agricultural machinery and equipment design. Although numerous studies have investigated the characteristics of different soil shear strengths, only a few of these works have paid attention to soils containing considerable quantities of rock fragments. To date, most studies on the effects of rock fragments on the shear strength have paid attention to the role of rock fragments with sizes >2 mm. The effects of rock fragments <2 mm in soil are generally ignored. Similar to rock fragments >2 mm, the presence of rock fragments <2 mm could also change the mechanical properties of soils. Thus, in the present study we evaluated the potential influence of <2 mm rock fragments on soil shear strength via an unconsolidated undrained (UU) triaxial compression test. Our results were as follows: (1) A certain quantity of <2 mm rock fragments presented in purple soils developed from clay rocks; and an appropriate quantity of <2 mm rock fragments could improve the shear strength of soils. (2) The different PSDs of soils containing <2 mm rock fragments mainly caused variations in the internal friction angle of soils. (3) The shear strengths of the two mudstone-developed red-brown and gray-brown purple soils was more sensitive to water than that of the shale-developed coarse-dark purple soil. As the soil water content increased from 9% to 23%, the changes in the cohesion, internal friction angle, shear strength, and the maximum principal stress difference were smaller in the coarse dark purple soil than in the two other soils. We therefore concluded that <2 mm rock fragments in purple soils exerted important effects on soil shear strength. A better understanding of the differences among the shear strength features of purple soils could help improve the design of agricultural machinery and equipment.

Keywords: Shear strength; Purple soils; Rock fragments; Particle size distribution (PSD); Soil water content; Triaxial test

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Introduction

Purple soil, classified as Regosols in the Food and Agriculture Organization (FAO) Taxonomy or Entisols in the United States Department of

Agriculture (USDA) Taxonomy, is formed in Triassic, Jurassic, Cretaceous, and Tertiary rocks or their purple-weathering products by intense physical and weak chemical weathering, and widely distributed in the Sichuan Basin. The weathering was significantly decreased during early pedogenic processes, thereby resulting in thin and high rock fragment contents (Zhang et al. 2011). In general, rock fragments refer to all mineral particles larger than 5 mm in diameter (Nyssen et al. 2002) or mineral particles larger than 2 mm (Van Wesemael et al. 1995a, b). The presence of rock fragments can affect the physical, chemical and hydrological properties of soil, such as its structure, texture, available water content, infiltration rate, and runoff susceptibility, and exert strong influences on the mechanical properties of soil (Poesen and Lavee 1994; Poesen et al. 1999; Isabelle et al. 2003). Rock fragments <2 mm in diameter are often present in purple soils because of the disintegration of highly weathered clay rocks and reclamation of Regosol lithic materials. Rock fragments <2 mm in diameter differ from the individual particles and soil aggregates <2 mm in diameter: the former consist of mineral particles less than a particular particle size (such as <0.25 mm, or even finer), and these particles stick together closely with small porosity during diagenesis (Zhao and Zhu 2001). Thus, research on other soils cannot be used to explain the mechanical properties of purple soil with <2 mm rock fragments.

Soil shear strength is one of the most important indicators of engineering design. Many engineering and laboratory tests have shown that shearing is one of the main types of structural damage affecting soil (Nam et al. 2011). In the engineering design process, the foundation bearing capacity and stability of the construction area must be studied and analyzed carefully. Meanwhile, soil shear strength is an important indicator of the stability of foundations. In studies of saturated soil, the Mohr-Coulomb strength theory can accurately determine shear strength values, as confirmed by experiments and in engineering practice (Chen and Fredlund 2003). The Mohr-Coulomb strength formula has also been used to calculate the shear strength of unsaturated soil before the mid-20th century. Then, research from different countries has sought to establish a theoretical and computational formula to describe unsaturated soil shear strength. The Bishop and Fredlund theories, for example, are commonly employed to resolve the problem of unsaturated soil shear strength; however, their formulas contain suction terms, which are difficult to be controlled and measured. Thus, the applications of these formulas are limited (Lu et al. 1997; Zhao et al. 2001; Ng et al. 2003; Ling and Yin 2007; Gu et al. 2015). As a result, the Mohr-Coulomb strength theory has been widely used to calculate the shear strength of unsaturated soil (Ni et al. 2013; Hu et al. 2013; Havaee et al. 2015).

Soil shear strength can be affected by various factors, including the soil type, particle size distribution (PSD), moisture, sodicity, matric suction, rock fragments, and so on (Hara et al. 2004; Chen et al. 2007; Wei et al. 2008; Hu et al. 2013; Li 2013; Sahin et al. 2015). In specific soil engineering, the soil density cannot be significantly changed. Firstly, given that the lithology and structure of the purple parent rock are fairly specific, this rock is a type of highly weathered soil parent material and the extent of its physical weathering is significant. Large quantities of rock fragments <2 mm in diameter are present in purple soils compared with other soils, and the PSD of natural-state purple soil changes rapidly, thereby affecting the resulting soil strength. Secondly, the annual rainfall in the study area is high but spatial and temporal distributions are uneven. Moreover, changes in the surface water or groundwater in the Three Gorges Reservoir (TGR) area can affect the soil water content and thereby influencing the shear strength of soil. Thus, relative to other factors, the impacts of rock fragments <2 mm in diameter, soil water content and PSD are particularly important (Wang et al. 2005; Ding and Lei 2007).

Studies have conducted on rock fragments, soil particle size ratio characteristics, and the water-sensitive features of different types of soil in different areas. For example, the pedogenetic capacity of rock fragments can be expressed by their content of <2 mm particles as weathered products of rock fragment disintegration (Wei et al. 2006). Results have indicated that rock fragments affect the soil's physical, chemical, hydrological, and mechanical properties, such as its structure, texture, available water content, infiltration rate, and runoff susceptibility (Poesen and Lavee 1994;

Poesen et al. 1999; Isabelle et al. 2003). Meanwhile, the presence of rock fragments can reduce soil water content (Zhang et al. 2011) as well as water and soil losses (Cerdà 2001). However, these fragments have no obvious effect on soil hydraulic conductivity in karst landscape areas (Li et al. 2008). The PSD studies have found that an increasing particle irregularity causes a decrease in stiffness but increases the sensitivity to the state of stress and the critical state friction angle (Cho et al. 2006). Graded sands possess lower cyclic resistance than uniform sands at the same relative density (Vaid et al. 1990). Improvements in gradation result in better occlusion between soil particles, which increases the soil shear strength (Jiang et al. 2009). Thus, the devastating of soil is less likely to develop in well-graded granular soils compared with poorly graded sands with the same relative density (Kokusho et al. 2004; Hara et al. 2004). In studies on the effects of soil water content on shear strength, Li et al. (2006, 2007) reported that soil water content was the main factor to affect the shear strength of loess, and soil deformation showed the characteristics of plastic deformation at higher soil water content. Brittle fracture may be occurred under dry conditions. The shear strength, cohesion, and internal friction angle of expansive soil and red clay decrease with increasing soil water content (Miao et al. 1999; Wang et al. 2011). Chen et al. (2007) and Hu et al. (2013) found maximum cohesion values of about 10%–13%. Zhou and Xu (2014) discovered that pore water pressure was mainly controlled by the shear stress level in a fixed principal stress direction test and a pure rotation test. The uniaxial compressive strength, elastic modulus, cohesion, and angle of internal friction decrease in red sandstone samples with increased numbers of freezing and thawing cycles (Yu et al. 2015). In summary, the soil shear strength could be significantly affected by rock fragments, soil particle size characteristics, and soil water content.

Considerably higher quantities of rock fragments (including <2 mm ones) exist in purple soils, unlike in other soils. Previous studies have consistently focused on >2 mm rock fragments, and <2 mm rock fragments are generally ignored. However, similar to >2 mm rock fragments, <2 mm rock fragments can also modify the mechanical properties of soils, including PSD and soil water characteristics. Therefore, using typical and representative purple clay rock-developed soils from the Sichuan Basin, our objectives were to address the effects of <2 mm rock fragments on such soil mechanical properties. Those soils included red-brown purple soils from the Suining Formation (J_3s) of the Jurassic period, gray-brown purple soils from the Shaximiao Formation (J_2s) of the Jurassic period, and coarse dark purple soils from the Feixianguan (T_1f) Formation of the Triassic period.

1 Materials and Methods

1.1 Description of the study area

The Sichuan Basin, which extends for 1000 km E–W and 500 km N–S, is located in southwestern China and has an area of 165,000 km^2 and elevations of 200–700 meters high. The Tibetan plateau lies to the west and to the north, the Yunnan Plateau extends to the south, and several hundred kilometres of mid-elevation hills lie to the east. The basin includes the central and eastern parts of the Sichuan province, as well as the Chongqing Municipality (Figure 1). The Sichuan basin is mainly covered by the red or purple rock series of the Trias–Cretaceous system and is also known as the “Red Basin” from which the purple soils are developed and formed. It has a sub-tropical monsoon climate with an annual average temperature and precipitation of 14°C–19°C and 1000–1400 mm (most between April and September), respectively.

1.2 Sampling and methods

The purple soils used in this study were developed from red-brown purple mudstones of the Suining Formation (J_3s), gray-brown purple mudstones of the Shaximiao Formation (J_2s) of the Jurassic system, and coarse-dark purple shale of the Feixiangguan Formation of the Trias system (T_1f), respectively. The soil samples were representatively collected based on the geological map of Chongqing with a scale of 1:500,000. The red-brown and gray-brown purple soils were collected from the Hechuan district of Chongqing, and the coarse-dark purple soil was from the Beibei

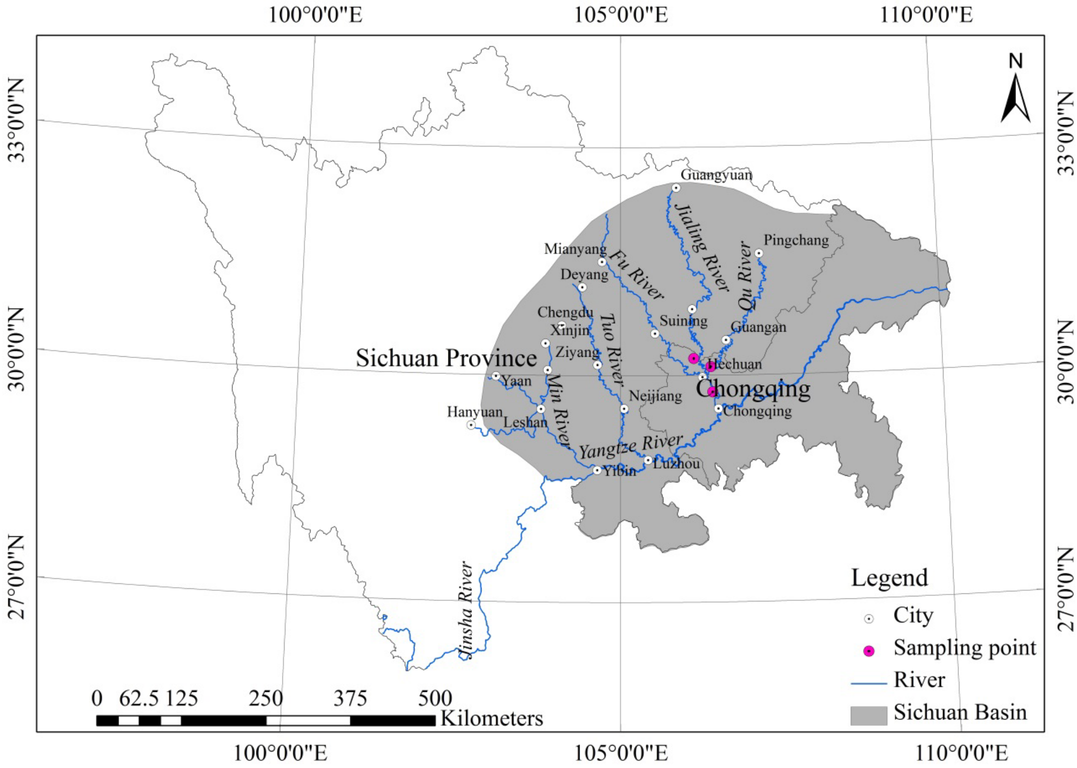

Figure 1 Location of the Sichuan Basin in China and distribution of sampling points.

Table 1 Descriptions of collected soil samples

Purple soil types	Sampling site	Lat. & Lon. [a]	Parent rock	Diagenetic environment	Land use	SL	TSL (cm)
Red-brown	Hechuan, Chongqing	30°12'28" N 106°06'25" E	Reddish purple thick mudstone of Suining Formation of early Late Jurassic (J_3s)	Sedimentated and diagenesised in vast shallow lake under aridic and torric weather	Mandarin	10°~15°	57
Gray-brown	Hechuan, Chongqing	30°06'24" N 106°23'58" E	Gray purple thick mudstone of Shaximiao Formation of Middle Jurassic (J_2s)	Sedimentated and diagenesised in river floodplain or near lake shore-shallow lake under more humid weather	Rapeseed-corn- sweet potato	10°~15°	62
Coarse dark	Beibei, Chongqing	29°50'33" N 106°27'35" E	Dark purple shale of Feixianguan Formation of Trias system (T_1f)	Sedimentated and diagenesised in shallow-sea under aridic, hot and high-pressure weather	Chili pepper-sweet potato	10°~15°	45

Notes: [a], the values of latitude and longitude are measured by the instrument of GPS; Lat. & Lon. represents latitude and longitude; SL represents slope of land; TSL represents thickness of soil layer.

district of Chongqing. All of the samples were from the hillside at a depth of 20–40 cm and weighted 10 kg. Gravel, plant roots, animal residues, and other impurities were removed. A detailed description of the samples is shown in Table 1.

To avoid discrepancies in soil dry density caused by field sampling, the experiment employed triaxial reconstituted soil samples. After naturally dried, the soil samples were ground (2mm), and then stored in airtight bags for further tests. The water content was measured from air-dried soils. To test the effects of the properties of soils and rock fragments on shear strength, basic physical properties were measured, shown in Figure 2, and Tables 2 and 3. To test the effects of PSD on shear strength, air-dried soils were selected using a three-level soil sieve (1.0–2.0 mm, 0.5–1.0 mm and <0.5 mm in diameter). Four groups of soil samples (A, B, C, and D) were configured with different mixing proportions of the three particle sizes mentioned above: 1:1:2 for A, 1:2:1 for B, 2:1:1 for C, and 1:1:1 for D. To test the water sensitivity of shear strength, seven different water contents (9%, 11%, 13%, 15%, 17%, 20%, and 23%) were pre-set based on the existing preparation method (Hu et al. 2013; Wang et al. 2014). The controlling samples for soil water measurement were prepared as follows: put the 2 mm sieved soils into a tray, spray the deionized water on the surface evenly, stir well to ensure the water is well-distributed, place the soil sample in an airtight bag at 4°C for 24 hours. The weight of water was calculated according to Eq. (1).

$$m_w = \frac{m_0}{1+w_0} \times (w - w_0) \qquad (1)$$

where m_w = weight of water; m_0= weight of air-dried soil; w = pre-set water content of soil sample; w_0 = water content of air-dried soil.

Based on the test requirements, the unconsolidated undrained (UU) triaxial compression test was conducted at three different pressures (100, 200, and 300 kPa) by using groups of samples with seven distinct soil water contents (9%, 11%, 13%, 15%, 17%, 20%, and 23%) with an dry density of about 1.65g/cm³ (Ni et al. 2012). The test specimens, with a diameter of 39.1 mm and height of 80 mm, were artificially configured. Three identical triaxial specimens were acquired to test soil water content, and the dry density error

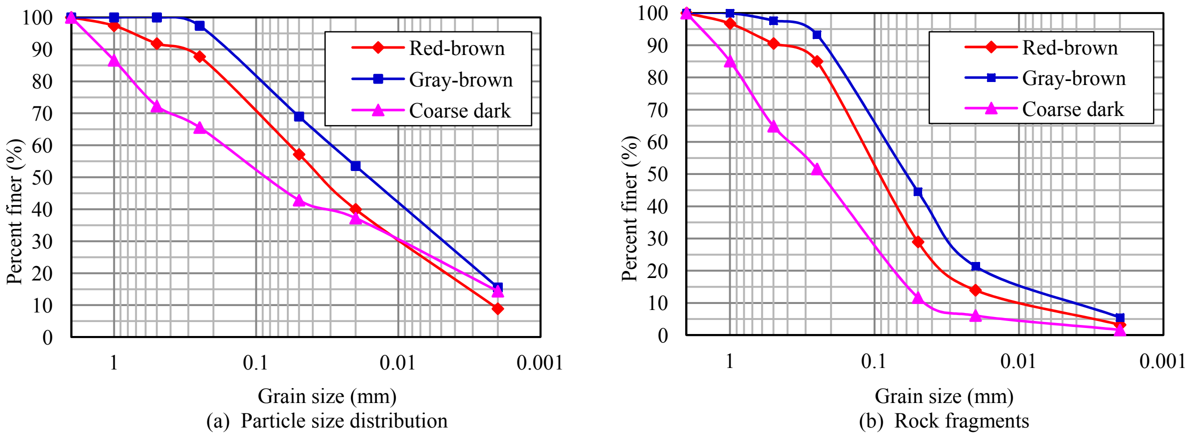

Figure 2 Particle size and rock fragments distribution curves for soil samples.

Table 2 Physical properties of purple soils

Purple soil types	Soil dry density (g/cm³)	Soil water content (%)	Plastic limit (%)	Liquid limit (%)	Plasticity index [a]	Cu [b]	Cc [c]	Dm [d]
Red-brown	1.35	23.6	18.1	32.7	14.6	26	1.12	2.68
Gray-brown	1.41	28.4	31.3	47.6	16.3	25	1.87	2.76
Coarse dark	1.37	25.8	30.7	45.9	15.2	144	0.73	2.75

Notes: [a], Plasticity index = Liquid limit - Plastic limit; [b] & [c], the values of Cu (Coefficient of uniformity) and Cc (Coefficient of curvature) are calculated according to the standard of GB/T 50145 – 2007 (2008); [d], Dm is the fractal dimensions of PSD of soils, and are calculated according to Du (2014).

Table 3 Physical properties of rock fragments (0.25~2 mm)

Purple rock fragment types	Specific gravity (g/cm³)	Bulk density (g/cm³)	Porosity (%) [a]
Red-brown	2.66	2.32	16.2
Gray-brown	2.69	2.35	15.6
Coarse dark	2.61	2.37	9.2

Note: [a], Porosity (%) = (1 - Bulk density/ Specific gravity) × 100.

was kept within ±0.1 g/cm³. At different confining pressures, the shear rate was 0.8 mm/min. If the peak of the shear test appeared, the shear process was continued until the axial strain was >20%. After the peak appeared, the test was continued until the axial strain was >15%. When the axial strain was 15%, the principal stress difference was regarded as the damage point (Yao et al. 2002; Zhan et al. 2003; Shi et al. 2010; Hu et al. 2013). Data were collected via a computer system coupled to a TSZ automatic triaxial equipment. Other statistical analyses were carried out using Excel 2010.

1.3 Basic physical properties of soil and rock fragments

The pipette method was used to measure soil PSD (Dane and Topp 2002). The water-washing method (Nyssen et al. 2002; Li 2006) was used to determine rock fragment distribution, and the specific gravity of the rock fragments was measured using a pycnometer (Dane and Topp 2002). The bulk density of the rock fragments was measured via the paraffin coating method (Dane and Topp 2002), and the liquid and plastic limits were measured using a liquid-plastic combine tester. The basic physical properties of the three types of purple soils are shown in Figure 2, Tables 2 and 3.

2 Results

2.1 Shear strength and properties of soils and <2 mm rock fragments

The ATSZ automatic triaxial apparatus was employed to measure the shear strength of the remoulded sample in the unconsolidated undrained shear test (UU). Seven soil water contents (9%, 11%, 13%, 15%, 17%, 20%, and 23%) were used for the soil water content test with a dry density of about 1.65 g/cm³. The physical properties and shear strength of the three purple soils are shown in Table 2 and Figures 3(a)–3(c). On the one hand, at three different normal pressures (100, 200, and 300 kPa), the shear strength of the three soils firstly increased and then decreased when the soil water content was increased from 9% to 23%. The optimum water contents of the red-brown purple soil, gray-brown purple soil and coarse dark purple soil were 11%, 13%, and 11%, respectively. When the soil water content was increased from 9% to 15%, the shear strength became higher in the gray-brown purple soil than in the two other soils. On the other hand, as the soil water content increased from 9% to 23%, the variation of shear strength increased with the increasing normal pressures. And the range of the shear strength variation was also obviously higher in the red-brown and gray-brown purple soil than in the coarse dark purple soil. When the normal pressures was about 100 kPa, the shear strength of the red-brown purple soil, gray-brown purple soil and coarse dark purple soil varied from 12 to 149 kPa, from 36 to 179kPa, and from 42 to 138 kPa, respectively (Figure 3(a)). When the normal pressure was about 200 kPa, the shear strengths varied from 19 to 197 kPa, 44 to 220 kPa, and 70 to 188 kPa, respectively (Figure 3(b)). When the normal pressure is about 300 kPa, the shear strengths varied from 26 to 255 kPa, 53 to 280 kPa, and 98 to 237 kPa, respectively (Figure 3(c)). These results reveal that the shear strength of the red-brown and gray-brown purple soils was more sensitive to water to change than that of the coarse dark purple soil.

The physical properties of the three purple rock fragments are shown in Table 3 and Figure 3(d). Table 3 revealed that the coarse dark purple soil was formed by neritic facies massive sedimentary rock, and its bulk density was the highest among all samples studied, but its specific gravity and porosity were the lowest. In terms of specific gravity and bulk density, the higher order ranked: gray-brown purple soil > red-brown purple soil. But the opposite was true for the values of porosity. Figure 3(d) also illustrated differences between PSD and rock fragments with "0.25 mm < grain size < 2.0 mm", the values of such differences in the red-brown purple soil, gray-brown purple soil and coarse dark purple soil were 2.73%, 4.12%, and 13.95%, respectively. These results thus revealed that the rock fragments and their properties had important influences on soil shear strength. High or low quantities of rock fragments would not improve the shear strength; thus, a moderate quantity of these fragments may be considered optimal.

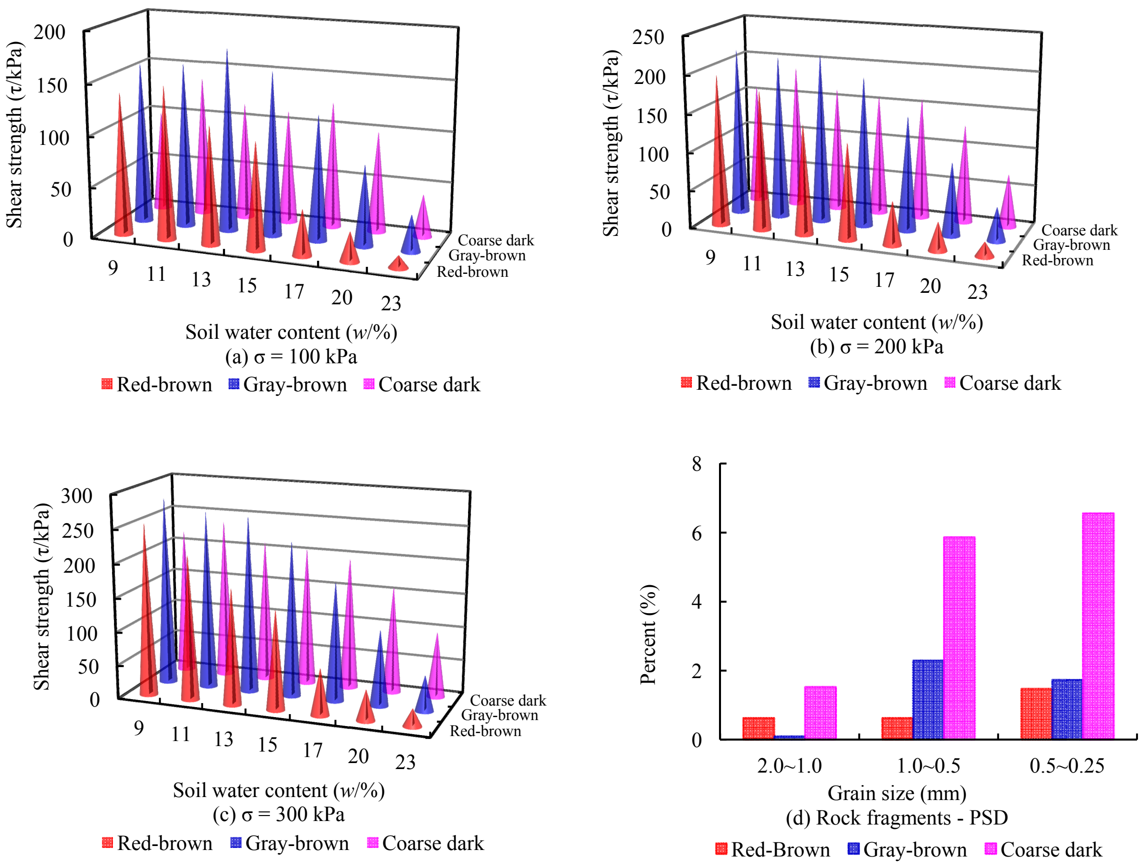

Figure 3 The soil shear strength and differences between rock fragments and soil particle size. (Figure 3(a), Figure 3(b) and Figure 3(c) represent the shear strength of the three soils under three normal pressures (100, 200, 300 kPa) and seven distinctive soil water contents (9%, 11%, 13%, 15%, 17%, 20% and 23%), respectively; Figure 3(d) represents differences between rock fragments and particle size according to the computation of Figure 2).

2.2 Effects of soil water changes on the shear strength of purple soils with <2 mm rock fragments

(1) Maximum principal stress difference

Based on the triaxial test results, the relationship between maximum principal stress difference and soil water content of is shown in Figure 4. At the same confining pressure, the maximum principal stress difference of these three purple soils decreased with increasing soil water content. When the soil water content was increased from 9% to 23% at a confining pressure of 300 kPa, the maximum principal stress differences between water content changes in the red-brown, gray-brown, and coarse dark purple soils decreased from 880, 1020, and 760 kPa to 48, 130, and 335 kPa, respectively. Thus, the decreases of the maximum principal stress differences in the red-brown and gray-brown purple soils were obviously higher than those in the coarse dark purple soil. And at the same confining pressure, the major principal stress on the triaxial shear test specimen surface decreased with increasing soil water content and the soil samples seemed easier to be damaged. When the soil water content was increased, the water on the surface of the soil particle functions as a lubricant, which could lead to a decrease in the angle of internal friction of the soil as well as sharp decreases in the cohesion of the particles. The increasing soil water content could further result in increases in the water film thickness and effective stress between soil particles. As a result, the soil shear strength could be decreased.

The relationship between the maximum principal stress difference and confining pressure of each sample is shown in Figure 5. At the same soil water content, the maximum principal stress

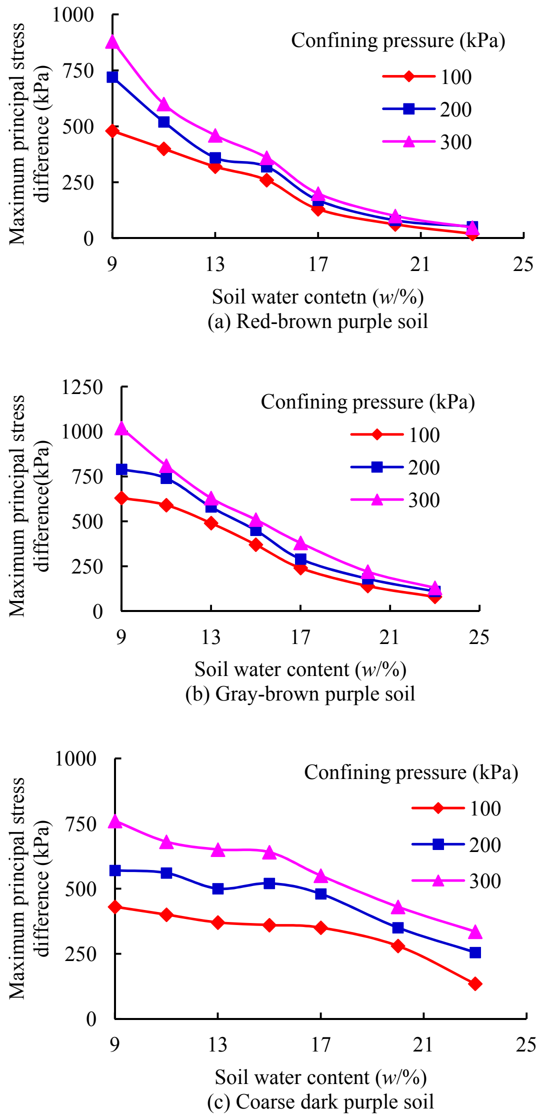

Figure 4 Relationships between maximum principal stress differences and soil water contents (Figure 4(a), Figure 4(b) and Figure 4(c) represent the relationships between the maximum principal stress differences and soil water content of red-brown purple soil, gray-brown purple soil and coarse dark purple soil, respectively).

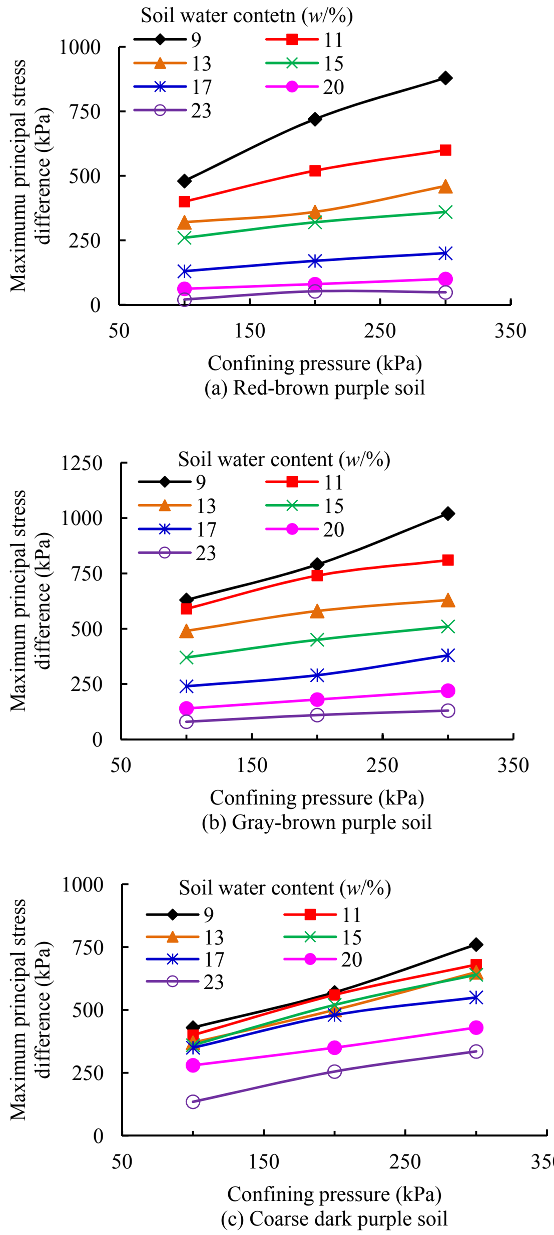

Figure 5 Relationships between maximum principal stress differences and confining pressure (Figure 5(a), Figure 5(b) and Figure 5(c) represent the relationships between the maximum principal stress differences and confining pressures of red-brown purple soil, gray-brown purple soil and coarse dark purple soil, respectively).

differences in the red-brown and gray-brown purple soils were increased with increasing confining pressure, but the increase was gradually decreased and eventually maintained at a stable level. When the confining pressure was increased from 100 kPa to 300 kPa at a soil water content of 9% or 23%, the maximum principal stress differences in the red-brown, gray-brown and coarse dark purple soils were increased from 480 to 880 kPa, 630 to 1020 kPa, and 430 to 760 kPa, or 20 to 48 kPa, 80 to 130 kPa, and 135 to 335 kPa, respectively. Thus, the maximum principal stress differences in all these three tested red-brown, gray-brown and coarse dark purple soils are sensitive to water, but the increase was less obvious in the coarse dark purple soil than in the two other soils.

(2) The Shear strength and its parameters

Figure 6 shows the shear strength envelope under different soil water contents. The shear strength of soil correlated with its initial water content. At any water content condition, the soil shear strength gradually increased with increasing normal pressure, although the increase rate differed among the soil samples.

In the red-brown purple soil developed from the mudstone, the shear strength increased with increasing normal pressure, but the increase trend was gradually decreased and eventually approached to plateaus with increasing water content (Figure 6(a)). The initial shear strengths at soil water contents of 9% and 15% were identical. When the normal pressure reaches 300 kPa, the shear strength at the 9% soil water content was significantly higher than those at other soil water contents. When the normal pressure was about 140 kPa, an intersection point was observed between the curves of the soil water contents of 9% and 11%. At this point, the shear strengths under the two soil water contents were also identical. When the soil water content was increased from 15% to 17%, the shear strength significantly decreased. The soil water content exerted different influences on the cohesion and internal friction angle of red-brown purple soil. For instance, when the soil water content was increased from 9% to 11%, the increase trend of the shear strength became significantly slower, and the initial shear strength was increased to its maximum value. Thus, the critical water content of red-brown purple soil was 11%. When the soil water content was increased from 11% to 23%, the shear strength and the slope of shear strength envelopes were decreased with increasing soil water content. Meanwhile, when the soil water content exceeded 11%, the maximum limit shear stress was decreased with increasing soil water content. In addition, the influence of normal pressure on the shear plane was gradually decreased, thereby making the soil more prone to be damaged. Moreover, then the soil water content was increased from 15% to 17%, the shear strength obviously decreased. Thus, if soil water content exceeded 15%, the soil became obviously damaged.

In the gray-brown purple soil developed from the mudstone, the shear strength was increased with increasing normal pressure, but the increase trend gradually decreased and eventually

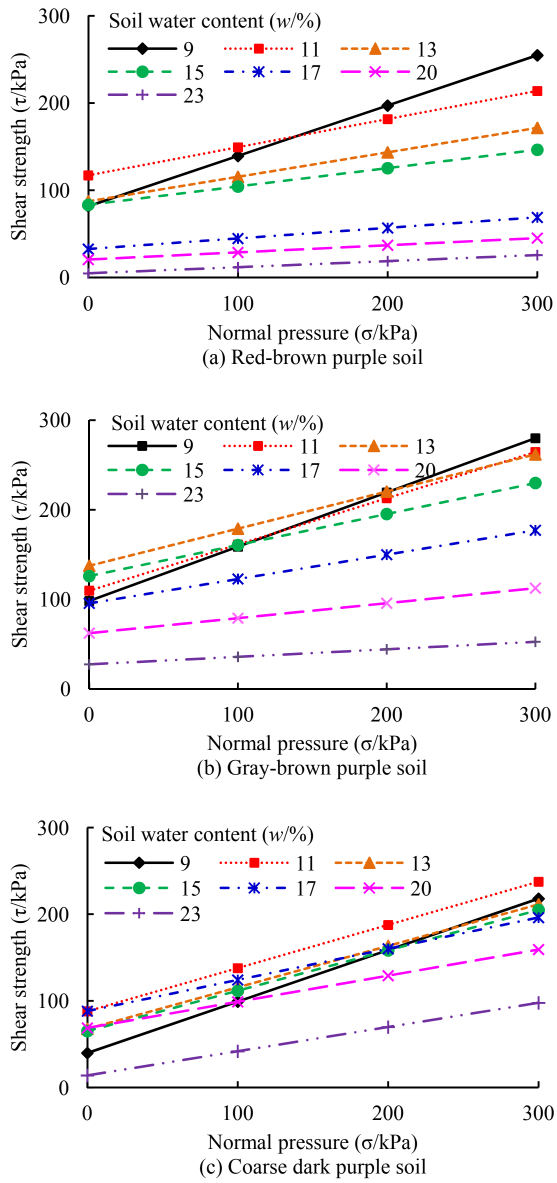

Figure 6 Shear strength envelopes under different soil water contents (Figure 6(a), Figure 6(b) and Figure 6(c) represent the shear strength envelope of red-brown purple soil, gray-brown purple soil and coarse dark purple soil under different soil water contents, respectively).

approached to plateaus with increasing soil water content. When the normal pressure reached to 300 kPa, the shear strengths were decreased with increasing soil water contents, and no obvious changes in the initial shear strength (Figure 6(b)). When the normal pressure was about 200 kPa, an intersection point was observed between the curves of the soil water contents of 9% and 13%. At this point, the shear strengths under the two soil water contents were identical. The above analyses showed that changes in the shearing strength in the gray-brown purple soil with changes in soil water content were similar to those in the red-brown purple soil. The curves of the shear strength firstly increased and then decreased, and the critical water content was 13%. When the soil water content exceeded 15%, the shear strength was significantly decreased with increasing soil water contents. When the soil water content was increased from 13% to 23%, the shear strength and the slope of the shear strength envelopes were decreased with increasing soil water contents. Therefore, when the soil water content was higher than 13%, the maximum limit shear forces were decreased with increasing soil water contents. And the influence of normal pressure on shear plane gradually decreased, thereby making the soil more prone to damage.

In the coarse dark purple soil developed from the shale, the shear strength was increased with increasing normal pressure, but no obvious changes in the increase trend (Figure 6(c)). The initial shear strengths at 11% and 17% soil water contents were similar but higher than other initial shear strengths observed. These results showed that two peaks of changes were appeared in the shear strengths with the soil water content curve in the coarse dark purple soil. When the normal pressure was increased from 0 kPa to 300 kPa, the shear strengths were significantly higher at soil water content of 11% than at other soil water contents. When the soil water content was increased from 20% to 23%, the shear strength was significantly decreased. Thus, if the soil water content exceeded 20%, the soil damage became more obvious. The above analyses showed that soil water contents exerted different influences on the cohesion and internal friction angle and changes in the shear strength of coarse dark purple soil with soil water contents differed from those of red-brown purple soil.

Cohesion (c) and internal friction angle (φ) are the two basic indicators of soil shear strength. When the soil water content was changed, the change rules of the cohesion and internal friction angle of the three purple soils differed from each other. As shown in Figure 7(a), the cohesion of the red-brown purple soil was firstly increased and then decreased. When the soil water content was increased from 9 to 11% or 11 to 23%, the cohesion was increased from 81.7 to 117.1 kPa or decreased from 117.1 to 4.8 kPa. Thus the critical water content is 11%. The results of the curve fitting showed that when $9\% < w \leq 11\%$, $c = 17.70w - 77.60$($R^2 = 1.00$) and when $11\% < w \leq 23\%$, $c = 0.43w^2 - 24.26w + 333.57$($R^2 = 0.95$). Similar to these changes in the red-brown purple soil, the cohesion of the gray-brown purple soil was firstly increased and then decreased. When the soil water content was increased from 9 to 13% or 13 to 23%, the cohesion was increased from 98.2 to 137.5 kPa or decreased from 137.5 to 27.2 kPa. Thus the critical water content was 13%. The results of the curve fitting showed that when $9\% < w \leq 13\%$, $c = 2.04w^2 - 35w + 248.16$($R^2 = 1.00$) and when $13\% < w \leq 23\%$, $c = -11.38w + 290.13$($R^2 = 0.99$). These changes in the coarse dark purple soil differed from those in the two other purple soils. The cohesion of coarse dark purple soil was irregularly changed with increasing soil water contents (Figure 7(a)). Along with the increase in soil water contents, the cohesion was firstly increased and then decreased,

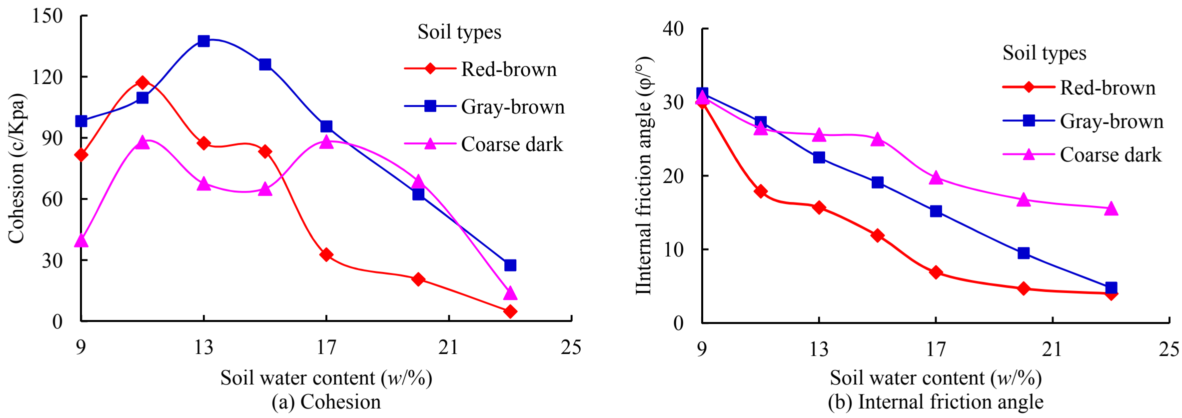

Figure 7 Curves of the cohesion/internal friction angle with changes in soil water contents.

and again increased, finally decreased. Thus, the two peaks were observed at soil water contents of 11% and 17% separately. When the soil water content was increased from 9 to 11% or 11 to 15%, the cohesion was increased from 39.9 to 88.0 kPa or decreased from 88.0 to 65.1 kPa. Furthermore, when the soil water content is increased from 15 to17% or 17 to 23%, the cohesion was increased from 65.1 to 88.2 kPa or decreased from 88.2 to 14.0 kPa. Thus the critical water contents were 11% and 17%. The results of the curve fitting showed that when 9% < w ≤ 11%, c = 24.05w -176.55 (R^2 = 1.00), when 11% < w ≤ 17%, c=2.71w^2 -76.05w + 596.74 (R^2 = 0.99), and when 17% < w ≤ 23%, c = -1.97w^2 + 66.30w - 470.53 (R^2 = 1.00). The cohesion of the coarse dark purple soil had smaller variation than that of the two other soils.

As shown in Figure 7(b), the internal friction angles were decreased with increasing soil water content. The curve fitting values showed that φ equalled to 4066$w^{-2.22}$ (R^2 = 0.97), −1.90w + 47.83(R^2 = 1.00) and − 1.09w + 39.73 (R^2 = 0.95) for the red-brown, gray-brown, and coarse dark purple soils. And the decrease of the internal friction angle was obviously smaller in the coarse dark purple soil than in the two other soils.

Based on the Mohr-Coulomb's law:

$$\tau_f=\sigma tan\varphi+c \qquad (2)$$

where τ_f = soil shear strength, kPa; σ = normal pressure, kPa; φ = internal friction angle, °; c = cohesion, kPa.

The shear strength formula was as follows for the red-brown purple soil,

$$\tau_f(w)=\begin{cases}\sigma tan\left(4066w^{-2.22}\right)+17.70w-77.60, & 9\%\leq w\leq 11\% \\ \sigma tan\left(4066w^{-2.22}\right)+0.43w^2-24.26w+333.57, & 11\%<w\leq 23\%\end{cases} \qquad (3)$$

for the gray-brown purple soil,

$$\tau_f(w)=\begin{cases}\sigma tan(-1.90w+47.83)+2.04w^2-35w+248.16, & 9\%\leq w\leq 13\% \\ \sigma tan(-1.90w+47.83)-11.38w+290.13, & 13\%<w\leq 23\%\end{cases} \qquad (4)$$

and for the coarse dark purple soil,

$$\tau_f(w)=\begin{cases}\sigma tan(-1.09w+39.73)+24.05w-176.55, & 9\%\leq w\leq 11\% \\ \sigma tan(-1.09w+39.73)+2.71w^2-76.05w+596.74, & 11\%<w\leq 17\% \\ \sigma tan(-1.09w+39.73)-1.97w^2+66.30w-470.53, & 17\%<w\leq 23\%\end{cases} \qquad (5)$$

2.3 Effects of PSD changes on the shear strength of purple soils with <2 mm rock fragments

To determine the effects of PSD on the shear strength of unsaturated purple soils, the air-dried soil was selected via a three-sieve screening method (1.0–2.0 mm, 0.5–1.0 mm, and <0.5 mm in diameter). Four groups of soil samples (A, B, C, and D) were configured with different mixing proportions of the above mentioned three particle sizes based on Table 4. Figure 8 shows the particle size distribution curves for formulated soil samples.

As shown in Figure 9, with increasing soil water content, the slopes of the shear strength envelopes of the different PSDs differed from each other for the three tested soils. The higher order of the slopes of the four groups ranked as follows: A>B>D>C for both the red-brown and gray-brown purple soils, D>A>B>C for the coarse dark purple

Table 4 Soil samples formulated with different mixing proportions of soil particles

Purple soil types	Particle size ratio [a]		Dry density (g/cm3)	Soil water content (%)	Cu [b]	Cc [c]
Red-brown	A	1:1:2	1.65	11	14	1.40
	B	1:2:1	1.65	11	15	1.35
	C	2:1:1	1.65	11	15	1.29
	D	1:1:1	1.65	11	15	1.32
Gray-brown	A	1:1:2	1.65	13	22	2.12
	B	1:2:1	1.65	13	25	2.07
	C	2:1:1	1.65	13	24	2.04
	D	1:1:1	1.65	13	24	2.08
Coarse dark	A	1:1:2	1.65	11	89	0.81
	B	1:2:1	1.65	11	135	0.77
	C	2:1:1	1.65	11	144	0.74
	D	1:1:1	1.65	11	121	0.83

Notes: [a], the weight ratio of the soil particle sizes of 1.0–2.0 mm, 0.5–1.0 mm and < 0.5 mm; [b] & [c], the values of Cu (Coefficient of uniformity) and Cc (Coefficient of curvature) are calculated according to the standard of GB/T 50145 – 2007 (2008).

soil. However, the intercept of the shear strength envelopes of different PSDs were similar. For the red-brown and gray-brown purple soils, with highest quantity of fine particles (<0.5 mm), the soil sample A had the largest shear strength; while with the highest quantity of coarse particles (1.0–2.0 mm), the soil sample C had the smallest shear strength. Meanwhile, with 25% fine particles (<0.5 mm), 50% mid-sizes particles (0.5–1.0 mm), and 25% coarse particles (1.0–2.0 mm), the shear strength was slightly higher in the soil sample B than in the soil sample D. Thus, in the red-brown and gray-brown purple soils, the higher the fine particle contents, the stronger their shear strength; while the higher the coarse particle contents, the lower their shear strength. For the coarse dark purple soil, a greater pattern of its shear strength ranked D>A>B>C. Thus in general, the higher the fine particle contents in coarse dark purple soil, the stronger its shear strength. Soil sample D is an apparent exception to these trends. At the optimum soil water contents, the shear strengths of formulated soils were higher than those of the soils

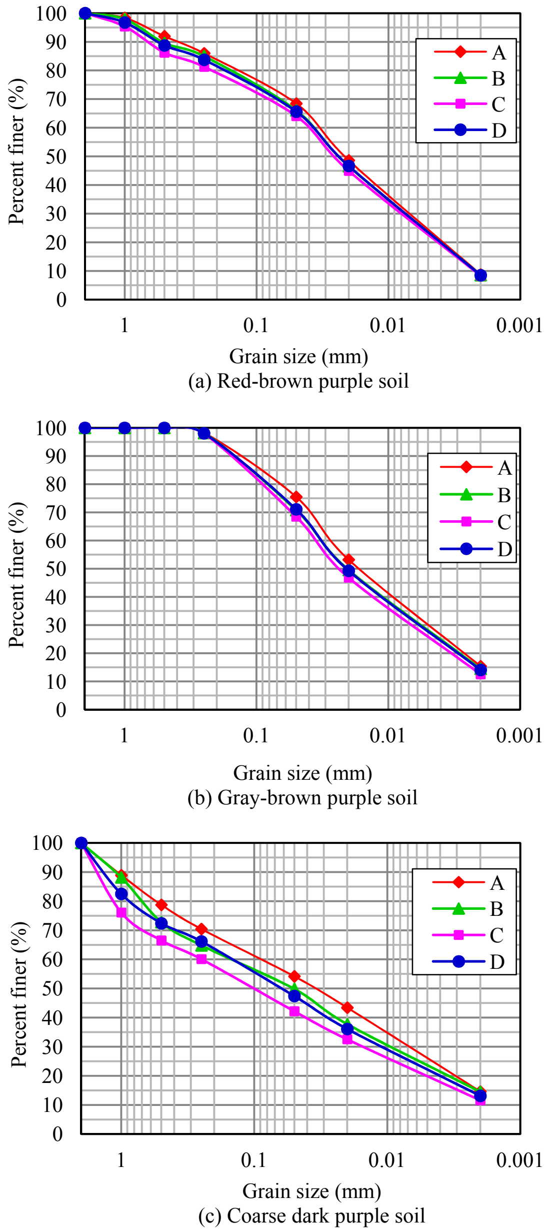

Figure 8 Particle size distribution curves for the formulated soil samples (Figure 8(a), Figure 8(b) and Figure 8(c) represent the particle size distribution curve of formulated red-brown purple soil, gray-brown purple soil and coarse dark purple soil, respectively).

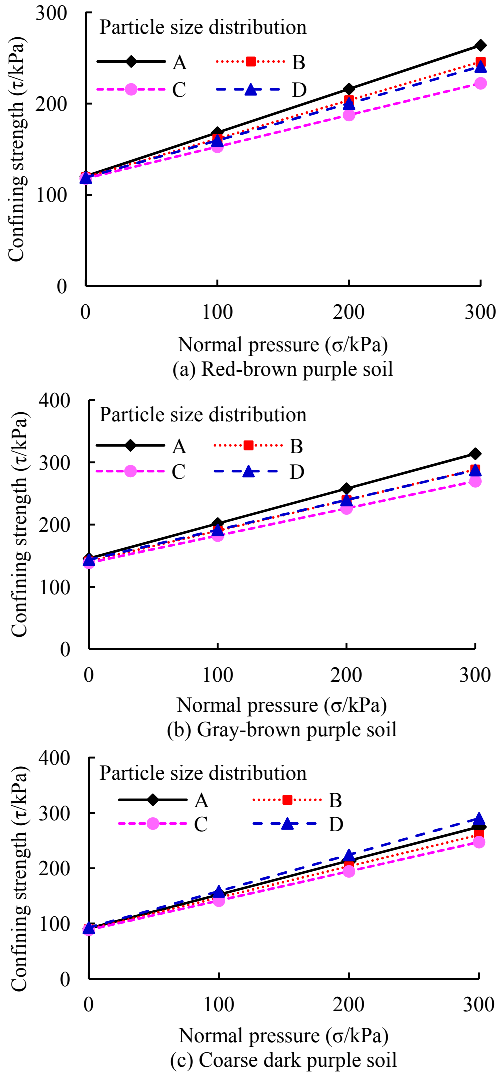

Figure 9 The shear strength envelopes of four different PSDs (Figure 9(a), Figure 9(b) and Figure 9(c) represent the shear strength envelope of red-brown purple soil, gray-brown purple soil and coarse dark purple soil under four different particle size distributions, respectively).

Table 5 The Shear strength parameters of different PSDs (Particle Size Distributions)

Purple soil types	DD (g/cm^3)	SWC (%)	Cohesion (c/kPa)				Internal friction angle (φ /°)			
			A	B	C	D	A	B	C	D
			1:1:2	1:2:1	2:1:1	1:1:1	1:1:2	1:2:1	2:1:1	1:1:1
Red-brown	1.65	11%	120.3	119.2	117.9	118.9	25.6	22.9	19.2	22.1
Gray-brown	1.65	13%	145.7	141	138.7	143.5	29.3	26.2	23.6	25.7
Coarse dark	1.65	11%	91.1	89.9	88.6	92.5	31.5	29.6	27.9	33.4

Notes: DD represents dry density; SWC represents soil water content.

before formulated.

Among the PSDs tested, the shear strengths of the three purple soils exhibited clear differences. As shown in Table 5, the cohesion or internal friction angle were changed from 117.9 to 120.3 kPa or 19.2° to 25.6°, from 138.7 to 145.7 kPa or 23.6° to 29.3° and from 88.6 to 92.5 kPa or 27.9° to 33.4° in the red-brown purple soil, the gray-brown purple soil and the coarse dark purple soil, respectively. Based on these results, for each soil, the cohesion changes of the four groups of soil samples were not obvious. In short, the influence of PSD on the cohesion was insignificant, but on the internal friction angle was significant. The higher order of the internal friction angles of the four groups with different PSDs ranked as follows: A>B>D>C for the red-brown and gray-brown purple soils, while D>A>B>C for the coarse dark purple soil. And all internal friction angles obtained are higher than those of soil samples that were not screened. Therefore, the internal friction angle was mainly while the cohesion was slightly affected by the PSD. As a result, an adjustment of the size ratio of soil grains between 0.25 and 2.0 mm might improve the internal friction angle.

3 Discussion and Conclusion

3.1 A moderate quantity of <2 mm rock fragments can improve the soil shear strength

Purple clay with a large number of rock fragments is developed from purple clay rock. The properties of soils are greatly dependent on the parent rocks' properties. Therefore, the properties of the parent rock have important influences on the shear strength of the soil. An important step in the formation of soil from rock is weathering of the rock into smaller pieces (Yatsu 1988). Physical and chemical alterations of rocks and minerals at or near the Earth's surface, which are produced by biological, chemical and physical agents or their combination, cause adjustments towards an equilibrium state in the surface environment (Pope et al. 2002). In general, the clastic mineral particles in soil may be divided into the fine earth fraction (<2 mm in diameter) and the coarser fraction (>2 mm in diameter). Pedologists usually regard the fine earth fraction as the soil component, which can be divided into sand, silt, and clay based on particle size (Schaetzl and Anderson 2005), and the coarser fraction as rock fragments. Previous studies have consistently focused on the individual particles (PSD or texture of soil, >2 mm rock fragments) and aggregates. However, while <2 mm rock fragments are largely presented, their properties are very substantially different from those of individual particles, aggregates, and >2 mm rock fragments. For instance, (1) Single particles: In single particles, each grain behaves independently. These particles control the PSD of soil, which can be defined as a combination of clay, silt, and sand contents, and are often reduced to a textural class (Soil Survey Division Staff, 1993). Single particles are usually the smallest particles; thus, they cannot be further divided into smaller particles. (2) Soil aggregates: Soil aggregates are regarded as the basic units of the soil structure. An aggregate is defined by Martin et al. (1955) as "a naturally occurring cluster or group of soil particles in which the forces holding the particles together are much stronger than the forces between adjacent clusters". Soil aggregates are porous and have the stability of water, mechanics, chemistry, pH, and biology (Domzal et al. 1993). Soil organic matter is the major binding agent (Jastrow 1996). Compared with rock fragments and single-particle sand, aggregates have a lower density but higher porosity. (3) Rock fragments: These <2 mm rock fragments differ from >2 mm mineral particles and <2 mm aggregates. They consist of soil particles less than a specific particle size (such as <0.25 mm or even finer), and these soil particles stick together closely with low porosity and high density. Rock fragments can be formed by disintegration of highly weathered clay rocks or reclamation of Regosol lithic materials. In the past, these particles were treated as <2 mm aggregates. We can distinguish rock fragments from aggregates by measuring their density and porosity.

The results in the Section 3.1 confirmed that a specific quantity of <2 mm rock fragments (0.25–2.0 mm) was present in purple soils [Figure 3(d)] and that the composition of these <2 mm rock fragments was consistent with their parent rock. Results further indicated that shear strength was closely related to the bulk density, porosity, and quantity of the rock fragments. The quantity of rock fragments influenced the Cu (Coefficient of uniformity) and Cc (Coefficient of curvature) values, which reflected the gradation level of soil. Thus, well-graded soils had higher shear strengths than non-graded soils. For coarse particles, the area of contact was low, and the friction was high. The opposite was true for fine particles. A large number of clay particles would thus result in high cohesion. When the percentages of different particle sizes reach a specific ratio (the optimum PSD), the internal friction angle and cohesion would reach maximum, and the soil shear strengths hence also reached their maximum. Therefore, a moderate quantity of <2 mm rock fragments would improve the shear strength of soil.

3.2 PSD changes in soil containing <2 mm rock fragments mainly affect their internal friction angle

At optimum soil water contents, the soil shear strength was higher after formulation than before formulation. The internal friction angle or the cohesion was mainly or slightly affected by the PSD. In the formulated soil samples with different PSDs, their coarse particles are significantly affected by the formulation process, whereas the <0.002 mm clay particles are only slightly affected (Figure 8). Therefore, when the soil water content is fixed at the optimal value, the forces between particles (such as the Coulombic forces, van der Waals forces, cementation forces, infiltration pressure, and water film bonding forces) could not be significantly changed. Hence, the cohesion, rather than the internal friction angle, was only slightly affected by the PSD (Chang and Hicher 2009). In the coarse particles, the contact area is small and the friction is high, while the opposite is true for fine particles. The internal friction angle could approach to its maximum when the percentage of different particle sizes reached to a specific ratio (the optimum PSD). Thus, at the optimum soil water content, the soil shear strength would reach to its optimal value because the cohesion remains nearly constant.

Among the four PSDs studied, the shear strengths obviously varied in the three purple soils (Figure 9). For red-brown and gray-brown purple soils, with the highest quantity of fine particles, the soil sample A from the red-brown and gray-brown purple soils exhibited the largest shear strength. In contrast, with mixed quantity of particles, the soil sample D from the coarse dark purple soil had the largest shear strength. The soil particle compositions differed among purple soils with different geological developments, which might explain the different effects of PSD on the purple soils [Figure 2(a)]. Before formulation, the coarse particles (0.25–2.0 mm) of nature soils were significantly different. The coarse dark purple soil showed the highest coarse particles content followed by the red-brown purple soil and the gray-brown purple soil. Therefore, the optimal PSD of coarse dark purple soil differed from that of the two other soils after soil sample formulation.

3.3 The shear strength of mudstone-developed soil is more sensitive to water than that of shale-developed soil

Results showed that the shear strength of purple soils was sensitive to soil water content, and different soils developed from different parent rocks had their own water sensitivity. In unsaturated soils, the cohesion and internal friction angle were substantially affected by changes in soil water contents (Mitchell 1993; AI-Shayea 2001; Goebel et al. 2004; Gitau et al. 2006; Scholtès et al. 2009). Previous studies have showed that the cohesion firstly increased and then decreased with increasing soil water contents, and the critical water content was about 11%. When the soil water content exceeded 11%, cohesion began to be rapidly decreased, and the unsaturated shear strength was thus significantly decreased (Xie et al.

1999; Xie 2001). The results in the present paper differed from those described above. The cohesion in the red-brown purple soil was consistent with the above-mentioned studies while the critical water content of the gray-brown purple soil water was 13% instead of 11%. In the coarse dark purple soil, two peaks of the cohesion were observed at soil water contents of 11% and 17%. For soils with different geological developments, the influences of environment, climate, element migration, and weathering degree on the internal structure of the particle and interparticle forces differed, and these differences might account for the variations observed in the present study.

The shear strength of soil mainly contains two sides, i.e. the cohesion and internal friction angle, which are strongly affected by soil water content (Mitchell et al. 2005; Chen et al. 2007; De Jong et al. 2010). The cohesion is a result of the combined effects of the attractive and repulsive forces between soil particles. In this study, for the red-brown and gray-brown purple soils, when the soil water content was increased from 9% to 11% (the former soil) or 13% (the later soil), the cohesion forces were increased, possibly due to the increased attractive forces between soil particles. At this time, from the consideration on the micro level, the attractive forces between soil particles are mainly the long-range van der Waals force, therefore the soil cohesion force could be strengthened (Chen et al. 2004; Gu and Sun 2005). However, when the soil water content exceeded the critical water content (11% or 13%), the water films around soil particles surface might become thicker, thus the lubrication between soil particles would become important, leading to a decrease of the soil cohesion force. On the other hand, the increase of soil water content could also result in the dissolution of cementing material in the soil, and hence the soil cohesion force decreased (AI-Shayea 2001).

The cohesion changes in the red-brown and gray-brown purple soils with increasing soil water content can be well explained by the discussion above. However, properties of the coarse dark purple soil differ from the two other soils. As the red-brown and gray-brown purple soils are developed from mudstone, whereas the coarse-dark purple soil is developed from shale. For instance, the coarse dark purple soil had a large quantity of <2mm rock fragments being mixed in soil, as showing in Figure 3(d). And the rock fragments mixed in coarse dark purple soil had a lower porosity but a higher bulk density than those of the two other soils (Table 3), leading to a distinctive soil water characteristics in this coarse dark purple soil. Such differences might result in less sensitivity of the shear strength in the coarse dark purple soil. Thus, as the soil water content increased from 9% to 23%, the variations of the cohesion, internal friction angle, shear strength, and the maximum principal stress difference of the coarse dark purple soil were smaller than those of the two other soils. Based on these analyses, the shear strength could be significantly affected by the parent rock, forming environment, <2 mm rock fragments, PSDs, and so on. Therefore, different soils should be differently treated when analyzing their soil shear strength. As the soil water content increased, the water film on the soil particle surface became thicker. Thus, the lubrication between soil particles was increased (Mitchell 1993), and the relative sliding friction resistance under the external forces of soil surface was decreased. Finally, the internal friction angles were decreased with increasing soil water contents. The results were in accordance with the previous studies (Ma et al. 2012; Ni et al. 2012, 2013; Hu et al. 2013; Wang et al. 2014).

Our findings confirm that purple soils contain a large number of rock fragments that can affect their PSD and shear strength. Changes in PSD mainly affect the internal friction angle. The shear strength is less sensitive to water in the coarse-dark purple soil developed from shale than in the red-brown and gray-brown purple soils developed from mudstone. These results could provide useful information in the future design of agricultural machinery and equipment.

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