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Influence of Different pH and Clay Content on the Mechanical Properties of Red Clay

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Abstract

This study investigates the variations in shear strength parameters of red clay under different clay content and pH levels through direct shear tests. It analyzes the effects of normal stress, clay content, and pH on shear strength, cohesion, and the internal friction angle. The research reveals that with an increase in normal stress, the shear strength of the soil gradually increases under the same clay content and pH conditions. Under the same clay content, as the pH level becomes more acidic or alkaline, the shear strength of red clay decreases. Higher clay content in red clay results in greater shear strength under the same pH conditions. As pH becomes more acidic or alkaline, the internal friction angle and cohesion of red clay decrease under the same clay content. Compared to its effect on cohesion, pH has a more pronounced impact on the internal friction angle.

Subject Areas

Civil Engineering

Keywords

Red Clay, Mechanical Properties, pH, Clay Content

1. Introduction

The Guangxi region has witnessed significant industrial development in recent years, marked by the completion of major projects such as Guangxi Liuzhou Steel Group, Liuzhou Chemical Industry Group Co., Ltd., and Liuzhou Zinc Product Co., Ltd. Additionally, rapid progress has been made in the construction of high-speed railways and highways, and traditional industries like tobacco and chemicals continue to exhibit stable growth, propelling Guangxi's economy into a phase of rapid expansion [1]. However, this industrial growth has led to the inevitable generation of various waste materials, including wastewater, exhaust gases, and residues, which, if released into the natural environment, can result in environmental pollution. When these waste materials are discharged into the soil, their acidic or alkaline properties can trigger reactions with the minerals in the soil, thereby altering the soil's internal structure and impacting some of its mechanical and physical properties [2]. This, in turn, poses a significant threat to the safety and stability of engineering constructions. Therefore, it becomes imperative to investigate the influence of pH levels on the mechanical properties of red clay.

Red clay represents a distinct type of soil with wide geographical distribution and an increasingly important role in engineering projects [3]. As the socio-economy continues to develop, numerous engineering ventures encounter specific challenges associated with the physical properties of red clay [4] [5]. Scholars from both domestic and international arenas have delved deeply into the mechanical characteristics of red clay [6] [7] [8]. Red clay, categorized as a type of carbonate rock, has evolved under specific climatic conditions following karst processes, imparting it with unique geological traits [9]. However, red clay exhibits certain unfavorable engineering attributes, including elevated moisture content and a propensity for shrink-swell behavior. These less-than-ideal engineering properties render it unsuitable for direct application in construction projects, often necessitating remedial measures before usage. Commonly employed improvement materials encompass lime, fly ash, and cement, among others [10] [11] [12]. Although the improvement effect of these chemical materials is good, there are also many shortcomings, such as the soil after the improvement of chemical materials is easy to harden, and the dry shrinkage and temperature shrinkage characteristics are very obvious, which is easy to lead to the cracking of the road base; Soil salinization, acidification will be more serious, biological traits will also deteriorate. The clay particles themselves are fine particles in the soil, and there is no pollution. Moreover, there has been limited exploration into the use of clay minerals for comprehending the mechanical properties of red clay. Hence, the present study investigates the influence of pH levels and clay content on the mechanical properties of red clay by introducing clay minerals. In particular, direct shear tests are conducted under varying stress conditions on red clay sourced from Guilin, with the goal of offering valuable insights for practical engineering applications.

2. Experimental Materials and Scheme

2.1. Selection of Test Materials and Preparation of Soil Samples

The soil utilized in this experiment was collected from a site approximately 4 meters below the ground near Guilin University of Electronic Science and Technology. Subsequently, the collected soil samples underwent air-drying and were sieved through a 2 mm sieve, as shown in **Figure 1**. Their fundamental physical properties were determined in accordance with the "Highway Geotechnical Test Code" [13]. According to the provisions of literature [13], Soil with plasticity index greater than 10 is cohesive soil. When the plasticity index Ip is greater than 17, it is clay. When the plasticity index Ip is greater than 10, but not greater than 17, it is silty clay. The results are presented in **Table 1**. Notably, the plasticity index of the soil is 20.7, surpassing the threshold of 17, thereby categorizing it as clayey soil.

Seven distinct pH solutions (pH values of 4, 5, 6, 7, 8, 9, and 10) were meticulously prepared using distilled water with a neutral pH of 7 as the base. Hydrochloric acid solution and sodium hydroxide powder were judiciously employed to fine-tune the pH to the desired levels, with each solution being securely sealed using plastic wrap. Subsequently, a uniform application of each of the seven pH solutions was administered onto 500g of soil via a spray bottle. Following a 24-hour period of sealed storage, the treated soils were adjusted to attain a moisture content of 27.5%. The test samples were concocted by combining red clay with varying proportions of clay minerals, yielding four distinct particle size distributions: −10%, 0%, 10%, and 20% clay content. The low-clay content soil was crafted by incorporating clay minerals into soil from which clay had been extracted.

2.2. Experimental Schemes

The experimental apparatus employed in this study was a strain-controlled direct shear apparatus, meticulously manufactured by Nanjing Soil Instrument

Table 1. Physical properties of the soil.

Specific Gravity	Maximum Dry Density (g/cm^3)	Optimum Moisture Content (%)	Natural Moisture Content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index
2.68	1.54	27.5	31.5	53.4	32.7	20.7

Figure 1. Test soil.

Factory Co., Ltd. According to the fast shear test of consolidation of middle soil in literature [13], the shear rate is set at 0.8 mm/min, and the shear loss is required within 3 - 5 min. However, in this test, the sample was always shear loss within 3min. In order to prolong the shear time and observe the shear failure of the test more clearly, the shear rate was set at 0.6 mm/min. And the completion of each test was determined upon the commencement of shear stress reduction. Four discrete normal stresses (100 kPa, 200 kPa, 300 kPa, and 400 kPa) were applied during the shear tests.

To account for the variables of pH and clay content, two distinct sets of experimental protocols were meticulously devised, as outlined in **Table 2**.

In the compaction process, a total of 105.61 g of moist soil was employed to fabricate ring samples with a dry density of 1.39 g/cm^3. Subsequently, the prepared specimens were placed within a humidity chamber, primed for use in direct shear tests.

3. Results and Analysis

3.1. Impact of Clay Content and pH Value on Shear Strength

The experimental data obtained from the direct shear tests underwent linear regression analysis to establish the relationship between the shear strength of red clay and normal stress under varying pH conditions. The results are depicted in **Figure 2**.

Figure 2 reveals that, under diverse normal stresses, the shear strength of red clay gradually diminishes as the pH shifts towards either acidity or alkalinity. The peak shear strength is attained when the pH of the red clay is neutral. Notably, red clay particles comprise a substantial quantity of oxygen-containing compounds, including Al_2O_3, Fe_2O_3, SiO_2, and others. When these free oxygen-containing compounds engage in chemical reactions with acidic or alkaline solutions, they interact with H^+ or OH^- ions, resulting in varying degrees of dissolution and leaching of the cementing material that binds the clay particles together. This reduction ultimately leads to a degradation of the original soil structure, with the effect becoming more pronounced as the acidity or alkalinity intensifies.

Exposure to strong acids or alkalis leads to an elevation in the concentration of H^+ or OH^- ions, culminating in the erosion of the interparticle cementing material. This erosion results in an enlargement of pore size, dispersion of particles,

Table 2. Experimental schemes.

Test Group	Clay Content (%)	pH Values	Number of Specimens
1	−10	4, 5, 6, 7, 8, 9, 10	28
2	0	4, 5, 6, 7, 8, 9, 10	28
3	10	4, 5, 6, 7, 8, 9, 10	28
4	20	4, 5, 6, 7, 8, 9, 10	28

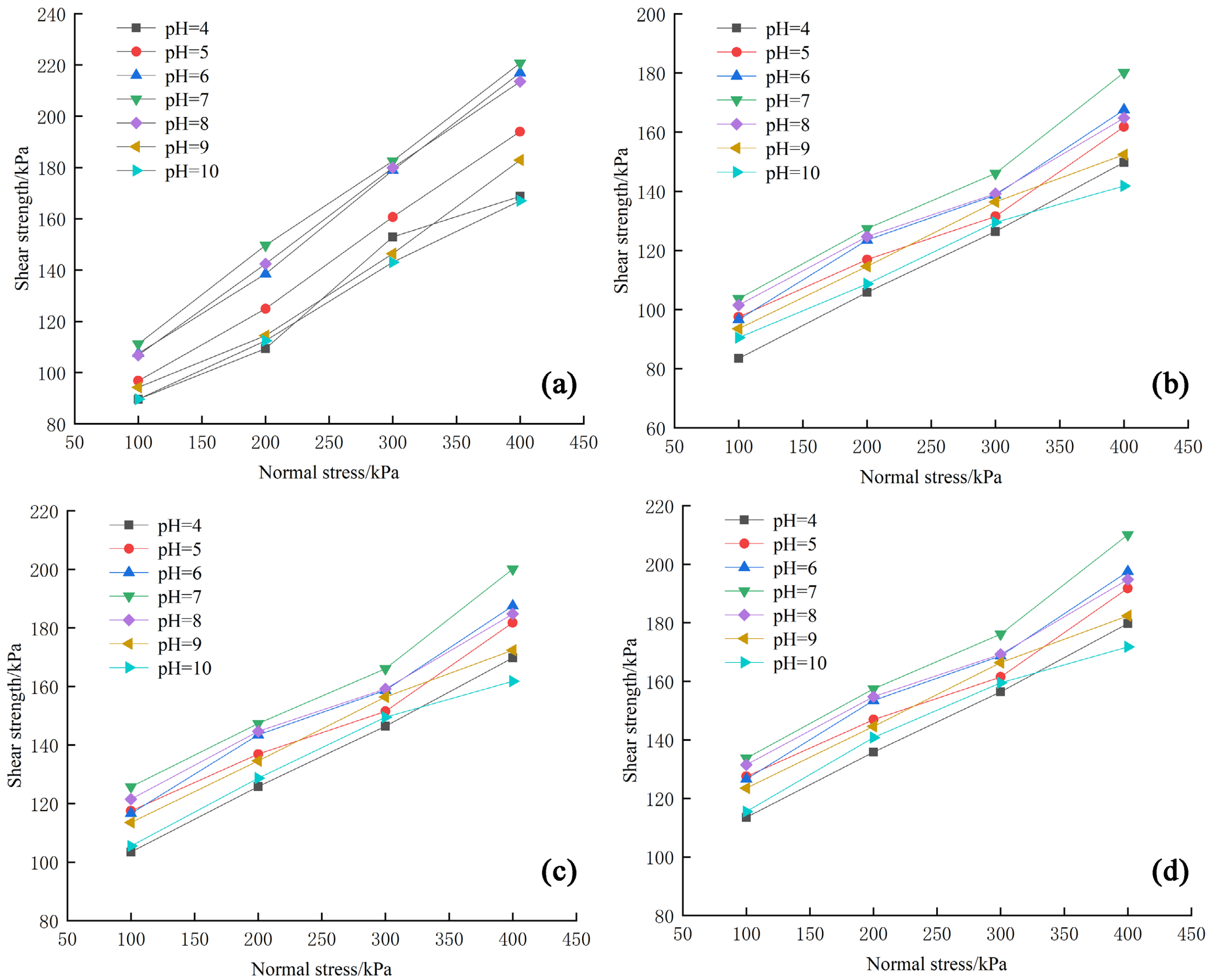

Figure 2. The variation of shear strength with normal stress under different pH conditions. (a) Clay content −10%; (b) Clay content 0%; (c) Clay content 10%; (d) Clay content 20%.

and a weakening of the soil structure. Strong acidic solutions have the capacity to dismantle the structural connections that exist between particle clusters and the internal mineral clays within particles. Conversely, when red clay interacts with weak acids or weak alkalis, only the outermost layer of particles experiences erosion, and solely a portion of the particle cementing material is eroded. Inter-particle bonding remains partially intact, consequently yielding a higher shear strength when compared to red clay specimens infiltrated by strong acids or strong alkalis. As the pH value continues to increase, the oxygen-containing compounds undergo successive decomposition, causing the cementing effect to gradually wane.

The presence of cementing material within red clay bolsters the structural integrity of the soil. Nonetheless, alterations in the solution medium conditions can lead to modifications in the physical properties of the cementing material, resulting in the structural disruption of the soil. Upon juxtaposing the four graphs, it becomes evident that with an elevation in clay content, the shear strength of the soil progressively ascends. Such as, as shown in **Figure 3**, under the same pH = 7, shear displacements of shear samples with different clay content gradually decrease with the increase of clay content. This phenomenon arises due to the increased presence of clay content, which correlates with an augmentation in oxygen-containing compounds within the soil. Consequently, more compounds engage in reactions with H^+ or OH^- ions within the acidic or alkaline medium. While only a fraction of the clay minerals participate in these reactions, the majority remains interspersed among soil particles, thereby preserving a degree of interparticle bonding. Consequently, soils characterized by higher clay content manifest superior shear strength in comparison to their counterparts with lower clay content.

3.2. Influence of Clay Content and pH Value on Cohesion and Internal Friction Angle

Figure 4 presents curves illustrating how shear strength parameters of the soil change with varying pH values for different clay content levels. From the graph, it is evident that as the pH of the infiltrating solution increases, both the cohesion and internal friction angle of the soil gradually decrease for a constant clay

Clay content -10% | Clay content 0% | Clay content 10% | Clay content 20%

Figure 3. Different shear displacements of shear samples with different clay content under the same pH.

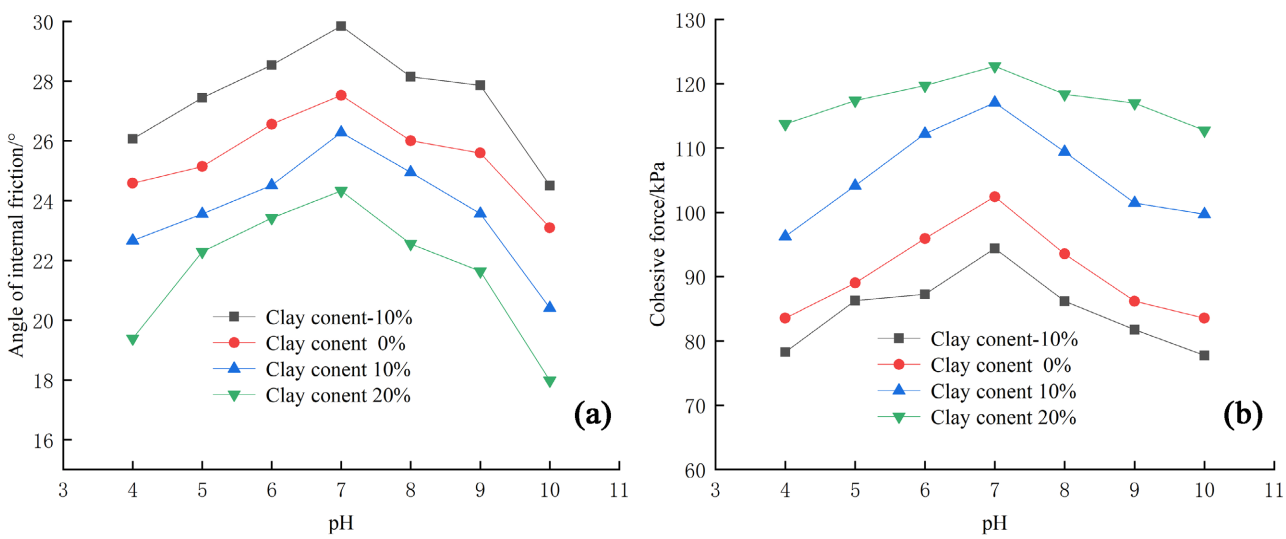

Figure 4. The variation of cohesion and internal friction angle with pH under different clay content. (a) The variation of internal friction angle with pH under different clay content; (b) The variation of cohesion with pH under different clay content.

content. Under the same pH conditions, the cohesion of the soil increases with higher clay content, while the internal friction angle decreases with increased clay content. When acidity or alkalinity becomes stronger, and acidity and alkalinity are relatively weak, the reduction in both cohesion and the internal friction angle is approximately the same. However, under strong acidic or alkaline conditions, the reduction in cohesion is significantly less than the reduction in the internal friction angle. This may be attributed to the fact that the internal friction angle is more sensitive to changes in the content of the cementing material affected by chemical reactions with acidity or alkalinity.

The cohesion (c) of the soil is determined by the degree of bonding between soil particles. An increase in the amount of cementing material between soil particles strengthens the bonding, resulting in increased cohesion. When red clay is contaminated by acidic or alkaline solutions, the cementing material between soil particles dissolves, reducing the bonding between soil particles and disrupting the soil structure. Therefore, as the acidity or alkalinity of the solution increases, the cohesion (c) of red clay gradually decreases. In **Figure 4**, under higher clay content, the decrease in cohesion is less pronounced compared to lower clay content, suggesting that as clay content increases, the interparticle bonding among red clay particles causes relatively minor chemical and physical damage to the soil, resulting in a smoother change in cohesion.

The internal friction angle (φ) of the soil depends on the internal friction between soil particles. A larger specific surface area of soil particles leads to greater internal friction between particles. However, when soil is exposed to acidic or alkaline solutions, the reduction in oxygen-containing compounds between particles decreases the specific surface area, leading to a decrease in internal friction between particles and a gradual reduction in the internal friction angle.

4. Conclusion

This study demonstrates the significant impact of clay content and pH on the shear strength, cohesion, and internal friction angle of red clay through direct shear tests on red clay samples with varying clay content and pH levels. The results indicate that, under identical clay content and pH conditions, an increase in normal stress leads to a gradual rise in the shear strength of the soil. Conversely, under the same clay content, a shift towards higher acidity or alkalinity results in reduced shear strength of red clay. Additionally, for soils with consistent pH conditions, higher clay content leads to increased shear strength. Moreover, as acidity or alkalinity increases, the internal friction angle and cohesion of red clay gradually decrease. Among these parameters, the internal friction angle exhibits greater sensitivity to changes in acidity or alkalinity compared to cohesion.

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Conflicts of Interest

The authors declare no conflicts of interest.

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