

Effect of Moisture Content on the Shear Strength of Locally Available Clayey Soil

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Abstract: This research paper investigates how varying moisture content affects the shear strength of a clayey soil collected from a construction site in Jodhpur, Rajasthan. The soil was classified as lean clay (CL) based on Atterberg limits testing. Standard Proctor compaction test determined the optimum moisture content as 18.2% with a maximum dry density of 1.74 g/cm³. Direct shear tests were performed on soil samples prepared at three moisture conditions: dry condition at 13.2%, optimum moisture content at 18.2%, and wet condition at 23.2%. The results showed that cohesion decreased from 48.3 kPa in dry conditions to 32.1 kPa at optimum moisture content and further dropped to 19.6 kPa in wet conditions. The angle of internal friction reduced from 27.4° in the dry state to 22.8° at optimum moisture content and then to 18.3° in wet conditions. The peak shear strength at a normal stress of 100 kPa was 98.7 kPa at dry conditions, 76.4 kPa at optimum moisture content, and 51.2 kPa at wet conditions. This study concludes that increasing moisture content significantly reduces both cohesion and friction angle, with cohesion being more sensitive to moisture changes. Therefore, moisture control during earthwork construction is essential for maintaining soil stability.

Keywords: Moisture content, shear strength, clayey soil, direct shear test

I. INTRODUCTION

Shear strength is one of the most critical parameters in geotechnical engineering because it directly controls the stability of slopes, bearing capacity of foundations, and safety of earth retaining structures (Terzaghi et al., 1996). For clayey soils, the presence and amount of water play a dominant role in determining how much load the soil can withstand before failure occurs (Das, 2019). When water enters the pores of a clay soil, it separates the clay particles, reduces the attractive forces between them, and often increases pore water pressure, all of which contribute to a reduction in shear strength (Lambe & Whitman, 2008).

In many construction projects across India and other tropical countries, engineers face the challenge of building on locally available clayey soils that undergo significant changes in moisture content due to seasonal rainfall or poor drainage (Ranjan & Rao, 2016). Numerous slope failures and foundation settlements have been attributed to the increase in moisture content above the optimum level during or after construction (Punmia et al., 2005). The motivation for this study came from observing repeated shallow slope failures along a newly constructed road embankment in the Jodhpur region, where the local clayey soil was used as fill material. It was suspected that improper moisture control during compaction and subsequent monsoon rains caused the shear strength to drop below safe limits.

The primary objectives of this study were to determine the basic index properties of the local clayey soil, establish the relationship between moisture content and shear strength using direct shear testing, and identify the critical moisture range where the soil experiences the most significant strength

loss. The findings of this study are intended to provide practical guidance for field engineers working with similar soils.

II. METHODOLOGY

The methodology followed a systematic laboratory testing program that began with soil collection and preparation, followed by index property testing, compaction testing, and finally direct shear testing under three different moisture conditions. All tests were conducted in the geotechnical engineering laboratory of the institution following Indian standards.

2.1 Soil Collection and Preparation

Disturbed soil samples were collected from a depth of 0.5 to 1.0 meters at an excavation site located in Jodhpur, Rajasthan. The soil was brownish in colour and appeared to be fine-grained with occasional fine sand particles. Approximately 50 kilograms of soil was extracted using a shovel and placed in sealed plastic bags to prevent moisture loss before transport to the laboratory. In the laboratory, the soil was spread on clean trays and air-dried for 72 hours at room temperature. After air drying, the soil was gently crushed using a wooden mallet to break down the larger clods without pulverising individual particles. The crushed soil was then sieved through a 4.75 mm sieve to remove any gravel-sized particles and ensure uniformity for the tests.

2.2 Index Properties Testing

The liquid limit of the soil was determined using the Casagrande apparatus as per ASTM D4318-17. Approximately 120 grams of soil passing the 425 micron sieve was mixed with distilled water to form a uniform paste.

The paste was placed in the Casagrande cup and spread to a depth of 10 mm. A grooving tool was used to create a standard groove, and the cup was lifted and dropped at a rate of two drops per second. The moisture content at which the groove closed over a distance of 12.7 mm after 25 blows was recorded as the liquid limit. The test was repeated three times, and the average value was taken.

The plastic limit was determined by rolling a small portion of the soil into threads of 3.2 mm diameter. The moisture content at which the thread just began to crumble was recorded as the plastic limit. The plasticity index was then calculated as the difference between the liquid limit and the plastic limit. Specific gravity was determined using a 50 mL pycnometer following ASTM D854-14. The pycnometer was filled with deaerated water and oven-dried soil, and the mass was recorded to compute the specific gravity.

2.3 Compaction Testing

The standard Proctor compaction test was performed according to ASTM D698-12. The air-dried soil passing the 4.75 mm sieve was mixed with varying amounts of water to achieve moisture contents ranging from 10% to 22% in increments of approximately 2%. For each moisture content, the soil was compacted in three equal layers inside a 101.6 mm diameter mould, with each layer receiving 25 blows from a 2.5 kg rammer dropped from a height of 305 mm. The wet density of the compacted soil was measured, and the dry density was calculated. The optimum moisture content was identified as the moisture content corresponding to the maximum dry density on the compaction curve.

2.4 Direct Shear Testing

Direct shear tests were performed using a shear box apparatus with a square box measuring 60 mm by 60 mm and 20 mm in height, following ASTM D3080-11. Three moisture conditions were selected for testing: dry condition, which was 5% below the optimum moisture content, optimum moisture content, and wet condition, which was 5% above the optimum moisture content. Based on the compaction test results, the optimum moisture content was 18.2%, so the dry condition was set at 13.2% moisture and the wet condition at 23.2% moisture.

For each moisture condition, the soil was mixed with the required amount of water and allowed to cure in sealed containers for 24 hours to ensure uniform moisture distribution. The soil was then compacted directly into the shear box in two layers to achieve the maximum dry density of 1.74 g/cm³ determined from the compaction test. Each sample was tested under three normal stresses of 50 kPa, 100 kPa, and 150 kPa. The shear load was applied at a constant strain rate of 1.25 mm per minute, and horizontal displacement and shear load readings were recorded at intervals of 0.25 mm until a total displacement of 10 mm or until the shear load reached a peak and then decreased significantly. For each test, the peak shear stress was recorded, and the Mohr-Coulomb failure envelope was plotted to determine the cohesion intercept and the angle of internal friction.

III. RESULTS

The results of all laboratory tests are presented in this section, beginning with the index properties, followed by the compaction characteristics, and finally the shear strength parameters under different moisture conditions.

3.1 Index Properties

The index property tests revealed that the locally available soil is a lean clay with moderate plasticity. The liquid limit was determined to be 46.2%, meaning that the soil changes from a liquid to a plastic state at this moisture content. The plastic limit was found to be 21.5%, indicating the moisture content at which the soil becomes too dry to remain plastic. Consequently, the plasticity index was calculated as 24.7%, which suggests that the soil has a moderate ability to undergo plastic deformation without cracking. The specific gravity of the soil solids was measured as 2.68, which is typical for most inorganic clayey soils. Based on the Unified Soil Classification System, with a liquid limit of 46.2% and a plasticity index of 24.7%, the soil was classified as CL, which stands for lean clay of low to medium plasticity.

3.2 Compaction Characteristics

The standard Proctor compaction test produced a bell-shaped curve when dry density was plotted against moisture content. As moisture content increased from 10% to 14%, the dry density increased because water acted as a lubricant, allowing soil particles to pack more closely together. The maximum dry density of 1.74 g/cm³ was achieved at a moisture content of 18.2%, which was therefore designated as the optimum moisture content. Beyond this point, as moisture content increased from 18.2% to 22%, the dry density began to decrease because water started to occupy space that would otherwise be filled by soil solids, and the pore water pressure began to resist further densification. The observed maximum dry density of 1.74 g/cm³ and optimum moisture content of 18.2% are typical values for lean clay soils in the western Indian region.

3.3 Shear Strength Parameters

The direct shear tests produced distinct failure envelopes for each of the three moisture conditions. For the dry condition at 13.2% moisture content, the peak shear stresses measured at normal stresses of 50 kPa, 100 kPa, and 150 kPa were 71.5 kPa, 98.7 kPa, and 126.2 kPa, respectively. When these values were plotted, and a best-fit straight line was drawn through them, the cohesion intercept on the shear stress axis was found to be 48.3 kPa, and the slope of the line gave an angle of internal friction of 27.4 degrees.

For the optimum moisture condition at 18.2% moisture content, the peak shear stresses decreased noticeably. At normal stresses of 50 kPa, 100 kPa, and 150 kPa, the measured peak shear stresses were 54.8 kPa, 76.4 kPa, and 98.3 kPa, respectively. The failure envelope for this condition yielded a cohesion of 32.1 kPa and a friction angle of 22.8 degrees. Compared to the dry condition, the cohesion

decreased by approximately 33.5%, while the friction angle decreased by about 16.8%.

For the wet condition at 23.2% moisture content, the shear strengths were substantially lower. The peak shear stresses at normal stresses of 50 kPa, 100 kPa, and 150 kPa were 37.4 kPa, 51.2 kPa, and 66.8 kPa, respectively. The cohesion dropped to 19.6 kPa, representing a reduction of 59.4% compared to the dry condition and 39% compared to the optimum moisture condition. The friction angle decreased further to 18.3 degrees, which is 33.2% lower than the dry condition and 19.7% lower than the optimum moisture condition.

A clear trend emerged from these results. As the moisture content increased from 13.2% to 18.2% and then to 23.2%, both cohesion and friction angle decreased consistently. However, the reduction in cohesion was more pronounced than the reduction in friction angle. At the highest moisture content tested, the soil lost more than half of its dry-state cohesion but retained about two-thirds of its dry-state friction angle.

IV. DISCUSSIONS

The results of this study demonstrate a clear and strong inverse relationship between moisture content and the shear strength parameters of the locally available clayey soil. This relationship has important implications for geotechnical engineering practice and explains many common field failures observed in clayey soils during or after rainy seasons.

The observed decrease in cohesion with increasing moisture content can be explained by the fundamental behaviour of clay-water interaction. In a dry or partially dry clay, the individual clay particles are held together by van der Waals forces and electrostatic attractions (Mitchell & Soga, 2005). When water is added, it forms thin films around the clay particles. As the moisture content increases, these water films become thicker and effectively separate the clay particles from direct contact with each other. The water molecules, being polar in nature, are attracted to the negatively charged surfaces of clay particles and form ordered layers that act as lubricants (Holtz et al., 2011). This separation greatly reduces the attractive forces between particles, which is manifested as a reduction in cohesion.

The decrease in the angle of internal friction with increasing moisture content, though less dramatic than the decrease in cohesion, is also significant. In clayey soils, the friction angle is not simply a function of particle-to-particle sliding friction as it is in sands. Instead, the friction angle in clays involves both sliding resistance and the resistance offered by the interlocking of particles and aggregates (Bolton, 1986). When moisture content increases, the water films around particles allow them to reorient more easily under shear stress, reducing the interlocking effect. Additionally, the effective stress between particles is reduced as pore water pressure builds up during shearing, even in a drained test setup.

Comparing the sensitivity of the two parameters to moisture change, it is evident that cohesion is more moisture-sensitive than the friction angle. The percentage reduction in cohesion from dry to wet conditions was 59.4%, whereas the reduction in friction angle was only 33.2%. This finding is consistent with published literature on clayey soils, which generally reports that cohesion is the parameter most affected by moisture variation (Fredlund & Rahardjo, 1993). The practical implication is that for slope stability or bearing capacity problems involving clayey soils, the primary concern with increasing moisture content should be the loss of cohesion, although the reduction in friction angle should not be ignored.

The peak shear strengths measured at a normal stress of 100 kPa decreased from 98.7 kPa at 13.2% moisture to 76.4 kPa at 18.2% moisture and further to 51.2 kPa at 23.2% moisture. This means that a moisture increase of 10 percentage points caused the shear strength to drop by nearly 50%. From a construction perspective, this is a critical finding because it quantifies how much strength can be lost if the soil is compacted at a moisture content higher than the optimum value. Many field compaction specifications allow a tolerance of plus or minus 2% around the optimum moisture content. The results of this study suggest that even a 2% increase above optimum moisture content would cause a measurable reduction in shear strength, and a 5% increase, such as might occur after heavy rainfall, would reduce the strength by approximately one-third.

The practical applications of these findings are numerous. For road embankments constructed with this clayey soil, it is essential to maintain the moisture content within two percentage points of the optimum during compaction. If the embankment is left exposed during the monsoon season, the upper layers will absorb moisture and lose strength, potentially leading to shallow slope failures. Therefore, proper drainage provisions and surface protection, such as grassing or geomembrane cover, should be provided immediately after construction. For shallow foundations built on this soil, the bearing capacity calculated using dry-season soil parameters may be unsafe during the wet season. Engineers should consider the worst-case moisture condition in design or specify foundation depths that extend below the zone of seasonal moisture variation.

Several limitations of this study should be acknowledged. The direct shear test uses a predetermined shear plane, which may not represent the actual failure surface in the field, where failure can occur along the weakest path through the soil mass. Additionally, the samples were prepared by compacting disturbed soil, which does not fully replicate the natural soil structure found in undisturbed field conditions. The study also did not measure pore water pressure during shearing, so the results are reported in terms of total stress rather than effective stress. Finally, the soil was collected from only one location, so the findings are specific to this soil type and may not be directly transferable to other clayey soils without similar testing.

V. CONCLUSIONS

This research successfully quantified the effect of moisture content on the shear strength of a locally available clayey soil from Jodhpur, India. The soil was classified as lean clay with a liquid limit of 46.2%, a plastic limit of 21.5%, a plasticity index of 24.7%, and a specific gravity of 2.68. The standard Proctor compaction test established an optimum moisture content of 18.2% and a maximum dry density of 1.74 g/cm³.

The direct shear tests revealed that increasing moisture content causes significant reductions in both cohesion and the angle of internal friction. At the dry condition of 13.2% moisture, the cohesion was 48.3 kPa and the friction angle was 27.4 degrees. At the optimum moisture content of 18.2%, these values decreased to 32.1 kPa and 22.8 degrees, respectively. At the wet condition of 23.2% moisture, the cohesion dropped to 19.6 kPa, and the friction angle fell to 18.3 degrees. Cohesion was found to be more sensitive to moisture increase than friction angle, losing nearly 60% of its dry-state value at the highest moisture content tested.

The peak shear strength at a normal stress of 100 kPa decreased from 98.7 kPa at dry conditions to 76.4 kPa at optimum moisture content and to 51.2 kPa at wet conditions, representing a 48% loss in strength over a 10 percentage point increase in moisture content.

Based on these findings, the following recommendations are made for geotechnical engineering practice. First, moisture content should be carefully controlled during compaction of this clayey soil, ideally within plus or minus 2% of the optimum moisture content. Second, drainage measures should be implemented on slopes and embankments constructed with this soil to prevent post-construction moisture increase. Third, foundation designs should consider the reduced shear strength that may occur during the wet season rather than relying on dry-season parameters. Fourth, field quality control should include frequent moisture content checks during earthwork operations.

For future research, it is recommended to conduct undrained triaxial tests with pore pressure measurement to obtain effective stress parameters, which would provide a more fundamental understanding of the moisture-strength relationship. Additionally, the effect of wetting-drying cycles on shear strength should be investigated because field soils experience repeated changes in moisture content rather than a single increase. Finally, laboratory tests should be complemented with field shear strength measurements to validate the findings under natural conditions.

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