

Physical Properties of Clayey Soil in the Development of Agricultural Strategies

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Abstract: Clayey soils are characterized by distinct physical properties that significantly affect agricultural productivity and soil management. Their fine texture, high water retention capacity, low permeability, and compact structure make them both challenging and beneficial for farming. This study examines the role of clayey soils in agriculture, incorporating both geological and agricultural perspectives. From a geological viewpoint, the mineral composition of clay, such as the presence of kaolinite, illite, and montmorillonite, influences how the soil behaves under various environmental conditions. These minerals impact water retention, nutrient availability, and the soil's response to tillage and compaction. In the context of agriculture, understanding these geological properties is essential for developing effective management strategies. For instance, while clayey soils can retain moisture, they can also become easily waterlogged or compacted, reducing root growth and limiting oxygen availability. Therefore, agricultural practices must be tailored to improve soil structure, enhance water infiltration, and prevent erosion. This research highlights the importance of integrating geological knowledge with agricultural strategies to address the specific challenges of clayey soils. By considering both the physical and mineralogical properties of clayey soils, farmers can adopt practices that optimize crop yield, minimize soil degradation, and promote sustainable farming. The study suggests that a combination of soil amendments, crop rotation, and careful irrigation practices can enhance the productivity and environmental sustainability of clayey soils.

Keywords: Soil texture, Agricultural strategies, Clayey soil, Soil management, Water retention.

I. INTRODUCTION

Soil is a critical natural resource that sustains life on Earth, playing a vital role in agriculture, ecology, and the environment. It is the topmost layer of the Earth's surface, a complex mixture of mineral particles, organic matter, water, and air. Soil provides the foundation for plant growth, regulates water

and nutrient cycles, and serves as a habitat for countless organisms. It is also a significant player in global carbon and nitrogen cycles, making it crucial for sustaining biodiversity and supporting ecosystems (Tarbuck et al., 2016). Among the many types of soil, clayey soils, or clay-rich soils, stand out due to their unique characteristics and diverse implications in both geological and agricultural contexts (Firoozi et al., 2016). These soils contain a high proportion of fine particles, typically smaller than 0.002 millimeters in diameter, which are primarily composed of clay minerals (Bergaya & Lagaly, 2006). The mineral composition of clay soils, including kaolinite, montmorillonite, and illite, determines their distinctive properties, such as high plasticity, water retention capacity, and low permeability (Do Nascimento, 2021).

From a geological perspective, clay-rich soils are formed through the weathering and breakdown of rocks (Taser & Metinoglu, 2005). Over time, physical, chemical, and biological processes break down the parent material into smaller particles, eventually resulting in the formation of clay minerals (Anikwe, 2000). The properties of these minerals, including their ability to hold moisture and nutrients, are crucial in shaping the soil's overall behavior (Phogat et al., 2015). Geologists study these properties to understand the processes involved in soil formation and to predict the long-term stability of clay soils in different environmental conditions (Lu et al., 2014). The importance of clayey soils in geology extends beyond soil formation (Adeyanju & Okeke, 2019). Clay minerals influence soil structure and its ability to retain water, which can impact erosion processes, land stability, and geological hazard management (Dhar & Hussain, 2019). For instance, clayey soils are often prone to swelling and shrinking with changes in moisture content, leading to land instability in areas with high clay content (Karkush & Yassin, 2020). These behaviors can have significant implications for construction, agriculture, and land management (Hassan et al., 2021).

In the context of agriculture, clay soils present both opportunities and challenges. Their ability to retain water makes them valuable for growing crops in regions with irregular rainfall patterns (Varghese & K, 2021). The fine texture of clayey soils

helps retain nutrients such as potassium, calcium, and magnesium, which are essential for plant growth (Sharma & Sharma, 2021). However, these soils also pose challenges for farmers due to their slow drainage and tendency to become compacted, limiting root growth and reducing the oxygen available to plants (Bahmed et al., 2019). The agricultural significance of clay soils can vary depending on local environmental conditions and soil management practices (Karkush & Ali, 2020). In areas where clay soils are prone to waterlogging, effective drainage systems are necessary to ensure the proper functioning of the soil (Rahgozar et al., 2018). Additionally, tillage practices must be carefully managed to prevent soil compaction and to enhance soil aeration, both of which are essential for maintaining healthy crops (GuhaRay et al., 2019). Farmers may also apply soil amendments, such as organic matter or gypsum, to improve soil structure and reduce the negative impacts of clayey soils (Pushpakumara & Mendis, 2022).

From a physical soil science perspective, clay-rich soils are of particular interest due to their unique physical properties (Ojuri et al., 2022). One key characteristic of clay soils is their high bulk density, which is the mass of soil per unit volume (Mohammed, 2018). Clay soil typically has higher bulk densities than other soil types, making them more prone to compaction and reducing their ability to store water and air (Amri et al., 2019). This makes understanding the physical properties of clay soils essential for optimizing agricultural practices and maintaining soil health (Haghsheno & Arabani, 2022). Another important physical property of clayey soils is their porosity, or the proportion of the soil volume that is made up of pore spaces. While clay soils have relatively low porosity compared to sandy soils, the size and distribution of the pores within the soil can affect water retention and drainage (Nikbakht et al., 2022). Clayey soils have small, fine pores that can hold water for extended periods, making them prone to waterlogging when saturated. The permeability of clay soils, or their ability to transmit water and air, is typically low, which can further complicate farming practices in these soils (Noaman et al., 2022). The water retention capacity of clay soils is both a benefit and a challenge (Zhu et al., 2019). While they can store large amounts of water, their slow drainage can lead to surface runoff and erosion in areas with heavy rainfall (Baldovino et al., 2018). Farmers must adopt irrigation and water management strategies to ensure that clay soil remains productive while avoiding excess water accumulation (Cherif et al., 2018). The use of raised beds, improved irrigation systems, and efficient water management practices can help mitigate water-related issues in clayey soils (Momeni et al., 2022).

The structural properties of clay soil, including their cohesion and compaction resistance, are also key factors in their agricultural suitability (Firoozi et al., 2016). The fine particles in clay soil bind together tightly, giving the soil its dense, compact nature. This compactness can impede root growth and hinder the movement of water and nutrients, making it difficult for plants to access essential resources (Do Nascimento, 2021). To address these challenges, soil management techniques such as deep tillage and crop rotation are often employed to enhance soil structure and improve plant growth. Soil erosion is another important consideration when dealing with clayey soils (Hassan

et al., 2021). While clay soils are less prone to wind erosion compared to sandy soils, they are highly susceptible to water erosion, especially on sloped terrains (Ghosh & Chakraborty, 2023). Heavy rainfall can cause the surface layers of clay soil to become dislodged, leading to sedimentation and the loss of topsoil (Velde, 1992). To combat erosion, conservation practices such as contour farming, terracing, and the use of cover crops are essential for protecting clayey soils and maintaining their fertility (Rahgozar et al., 2018). By integrating geological knowledge with agricultural practices, we can create effective strategies that address the challenges posed by clay soil and harness their potential for sustainable land use (Taser & Metinoglu, 2005). Understanding the fundamental properties of clayey soils and developing tailored approaches to their management will ensure that they continue to support agriculture, ecosystem health, and land stability in the future (Mohammed, 2018).

II. CLAYEY SOIL MINERALOGY

Clayey soils are a vital component of the Earth's surface and play a crucial role in geology, geotechnical engineering, agriculture, and environmental sustainability (Do Nascimento, 2021). These soils are primarily composed of fine-grained clay minerals, which are formed through the weathering of silicate rocks and other parent materials (Zhou & Keeling, 2013). The unique mineralogy of clayey soils significantly influences their physical, chemical, and mechanical properties, affecting everything from soil stability to crop productivity (Hajdarwish et al., 2013). Understanding the composition, structure, and behavior of clay minerals is essential for designing effective engineering solutions, improving agricultural soil management, and ensuring sustainable land use (Haghsheno & Arabani, 2022). Clay minerals exhibit high plasticity, water retention, and swelling potential, which make them both beneficial and problematic, depending on their application (Rahgozar et al., 2018). This paper explores the structural characteristics, classification, geotechnical significance, and sustainability considerations of clayey soil mineralogy in detail (Bahmed et al., 2019). Clay minerals belong to the phyllosilicate group, meaning they have a layered crystal structure composed of alternating tetrahedral and octahedral sheets (Lu et al., 2014). These sheets are formed by the arrangement of silicon, aluminum, oxygen, and hydroxyl ions, creating structures that define the physical and chemical behavior of clay minerals (Mohammed, 2018). Figure 1 provides a simplified example of clay mineral structure were described as (Do Nascimento, 2021):

Tetrahedral and Octahedral Sheets of Clay: Tetrahedral sheets consist of silicon (Si^{4+}) atoms surrounded by four oxygen (O^{2-}) atoms in a tetrahedral arrangement. These tetrahedra share oxygen atoms, forming a continuous sheet. In contrast, octahedral sheets are composed of aluminum (Al^{3+}), magnesium (Mg^{2+}), or iron ($\text{Fe}^{2+}/\text{Fe}^{3+}$) ions coordinated with oxygen or hydroxyl groups in an octahedral structure. The way these sheets are stacked determines the formation of different clay mineral groups, each with unique properties affecting plasticity, swelling behavior, and cation exchange capacity (CEC). Clay minerals are classified based on the ratio of tetrahedral to octahedral sheets in their structure. The three primary groups include kaolinite, illite, and smectite.

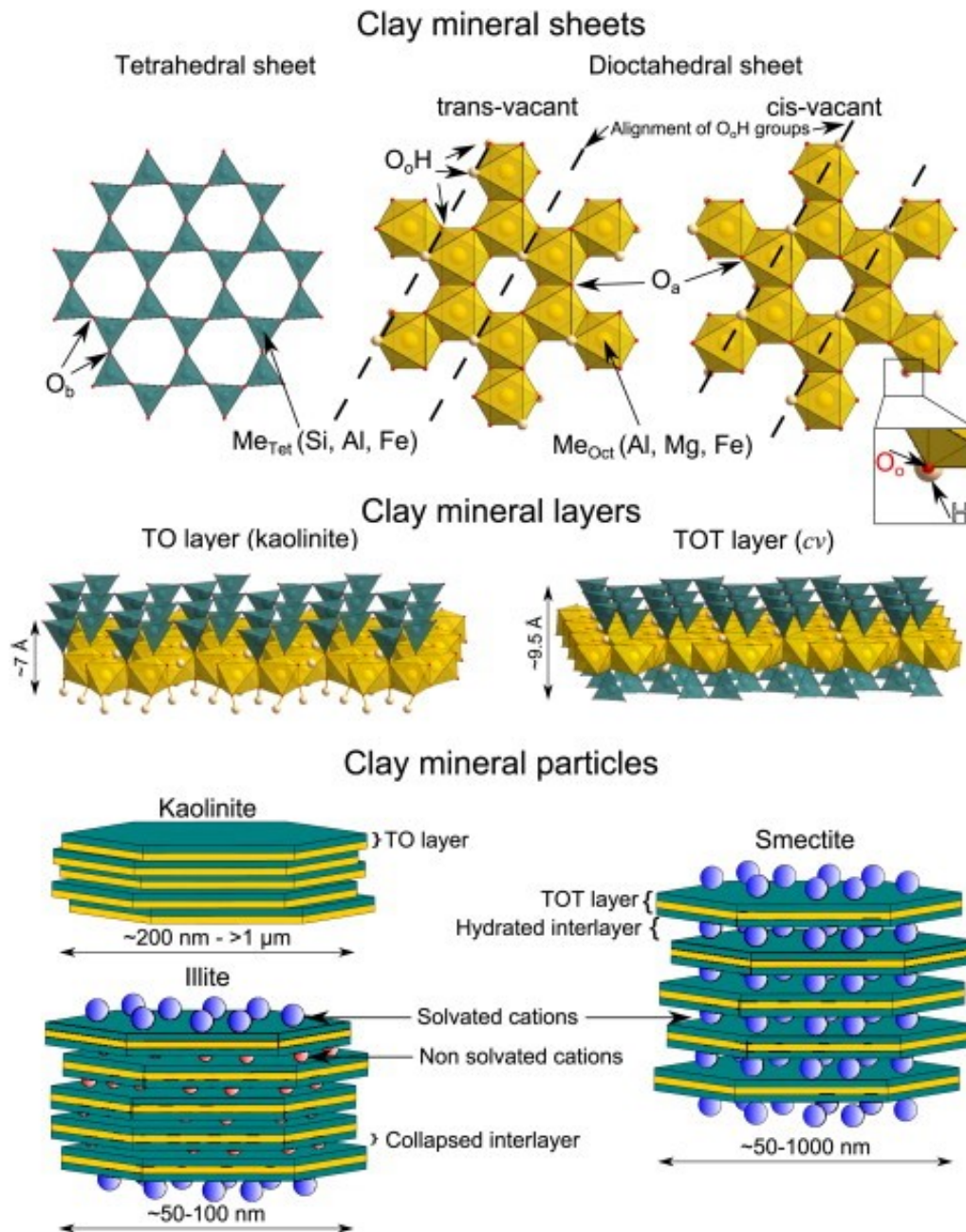


Fig. 1 Simplified structures for clay minerals (Tournassat et al., 2015)

The kaolinite group has a 1:1 structure, consisting of one tetrahedral sheet and one octahedral sheet. This stable structure is reinforced by strong hydrogen bonding between layers, making it non-expansive with low CEC (approximately 3-15 cmol/kg). Due to its excellent drainage properties, kaolinite is widely used in paper coating, ceramics, and pharmaceuticals. It is commonly found in highly weathered tropical soils, such as lateritic soils. The illite group follows a 2:1 structure, where two tetrahedral sheets enclose one octahedral sheet, with potassium (K^+) ions holding the layers together. This composition grants illite moderate CEC (around 15-40 cmol/kg) and partial expansiveness, making it more stable than smectite but more plastic than kaolinite. It is commonly used in brick-making, petroleum drilling, and soil amendments and is typically found in sedimentary rocks in temperate regions (Bahmed et al., 2019).

The smectite group, which includes montmorillonite and bentonite, also has a 2:1 structure but differs from illite due to its weak interlayer bonding. This characteristic allows water and cations to enter the structure, leading to significant swelling. Smectite minerals exhibit high CEC (approximately 80-150 cmol/kg) and are highly expansive, which can cause soil instability and drainage issues. Due to these properties, they are commonly used in drilling muds, geosynthetic clay liners, and landfill barriers. Smectite minerals are frequently found in volcanic ash deposits and marine sediments. Chlorite shares structural similarities with illite but includes an additional hydroxide layer, which minimizes expansion. Vermiculite, on the other hand, is highly expandable and excels in water retention, making it valuable for agricultural applications (Bahmed et al., 2019).

The mineralogical composition of clayey soils plays a critical role in their geotechnical behavior, significantly influencing the stability of structures, roads, and foundations (Firoozi et al., 2016). Understanding the properties of different clay minerals is essential for effective soil management, foundation design, and slope stabilization (Bahmed et al., 2019).

Shear Strength and Stability: The shear strength of clayey soils is largely dependent on their mineral composition. Soils rich in montmorillonite exhibit low shear strength and high plasticity, making them highly susceptible to landslides, slope failures, and differential settlement. Such soils require special engineering considerations, including reinforcement and stabilization techniques, to improve their load-bearing capacity. In contrast, kaolinite-dominated soils have lower plasticity and a non-expansive nature, providing a more stable foundation material with reduced susceptibility to deformation (Ghosh, 2013).

Swelling and Shrinkage Behavior: One of the most significant challenges associated with clay-rich soils is their swelling and shrinkage behavior, particularly in soils containing high amounts of smectite, such as montmorillonite. These expansive soils absorb large amounts of water during wet conditions, causing swelling, and shrink significantly upon drying, leading to severe structural damage to buildings, roads, and pavements. Common engineering solutions to mitigate these issues include lime stabilization, chemical treatments, soil replacement, and the use of geosynthetic reinforcements to control expansion potential and improve soil stability (Stoltz et al., 2012).

Permeability and Drainage: The permeability of clay soils varies significantly based on their mineralogical composition. Kaolinite-rich soils exhibit relatively high permeability, allowing for better drainage and making them suitable for construction projects that require stable subgrades with efficient water movement (Soga et al., 2017). In contrast, smectite-rich soils, due to their fine-grained nature and high swelling capacity, have low permeability, leading to excessive water retention, poor drainage, and increased risk of waterlogging. Proper drainage systems and soil amendments are often required to enhance water movement in such soils (Klimov & Klimova, 2022).

Clay mineralogy plays a fundamental role in agricultural productivity by influencing soil fertility, water retention, and nutrient availability. Soils rich in vermiculite and smectite have high CEC, which allows them to retain essential plant nutrients such as potassium, calcium, and magnesium. This enhances soil fertility and provides a sustainable nutrient supply for crops. Additionally, the water-holding capacity of clay minerals affects soil moisture availability, which is critical for plant growth, particularly in arid and semi-arid regions. However, excessive water retention in smectite-rich soils can lead to poor aeration and root suffocation, necessitating proper soil management practices such as aeration, organic matter addition, and drainage improvement to optimize plant growth conditions. Understanding the mineralogical composition of soils is essential for both geotechnical and agricultural applications, as it helps engineers, farmers, and land-use planners develop effective strategies for soil management, infrastructure development, and sustainable land use. By integrating geotechnical engineering, soil science, and environmental management, we can maximize the benefits of clay-rich soils while mitigating their challenges, ensuring their sustainability for future generations.

III. ENGINEERING OF IRANIAN CLAYS

Engineering geology of clays is a fundamental aspect of geotechnical engineering that plays a critical role in the design and stability of engineering projects. Clays, due to their unique properties, influence the performance of structures, foundations, and slopes, requiring engineers to thoroughly understand their behavior under different conditions (Gillott, 2012). The mineralogical composition of clays is characterized by fine-grained particles, which can be highly variable in terms of plasticity and cohesion. This variability necessitates detailed laboratory testing to determine key properties that affect the mechanical performance of clayey soils (Blyth & De Freitas, 2017).

One of the most important parameters in assessing clay behavior is the Atterberg limits. These limits define the critical water contents at which a clay transitions between solid, plastic, and liquid states, providing essential information about its workability and deformation potential (Karpinski & Szkodo, 2015). The Atterberg limits (comprising the liquid limit, plastic limit, and plasticity index), are crucial in classifying clays and predicting their behavior under loading. A high plasticity index, for instance, typically indicates clay that is highly sensitive to water content changes, which can lead to significant volume variations (Ahmed & Agaiby, 2020). As known, The Atterberg limits are fundamental indicators of the consistency and behavior of fine-grained soils, particularly clays, under varying moisture conditions. These limits (i.e., liquid limit, LL, plastic limit, PL, and shrinkage limit, SL), help classify soils based on their plasticity and predict their response to changes in water content. The liquid limit defines the water content at which the soil transitions from a plastic to a liquid state, indicating its flow potential under minimal stress. The plastic limit represents the moisture level at which the soil can be rolled into thin threads without breaking, marking the boundary between plastic and semi-solid behavior. Meanwhile, the shrinkage limit is the moisture content below which further drying no longer causes volume reduction, crucial for assessing soil shrinkage potential (Nikbakht et al., 2022).

Beyond classification, Atterberg limits provide valuable insights into the soil's engineering performance were used to identify and classify the clay types as provided in Figure 2. A high plasticity index ($PI = LL - PL$) suggests that the soil is highly reactive to moisture fluctuations, leading to significant swelling and shrinkage cycles that can compromise structural integrity. Expansive clays with high LL and PI values pose challenges in foundation design due to their potential for volumetric instability (O'Kelly, 2021). Conversely, soils with low plasticity exhibit more predictable behavior, making them preferable for construction purposes. Understanding these parameters enables engineers to anticipate soil-related hazards, such as differential settlement and cracking, particularly in regions with fluctuating groundwater levels (Žbik et al., 2015). By integrating Atterberg limit data with other soil properties, engineers can make informed decisions about material suitability and ensuring durability. Another key characteristic of clays is their compressibility. Clays are known to undergo significant consolidation under sustained loads. This compressibility is influenced by factors such as initial void ratio, water content, and the clay mineralogy (Blyth & De Freitas, 2017).

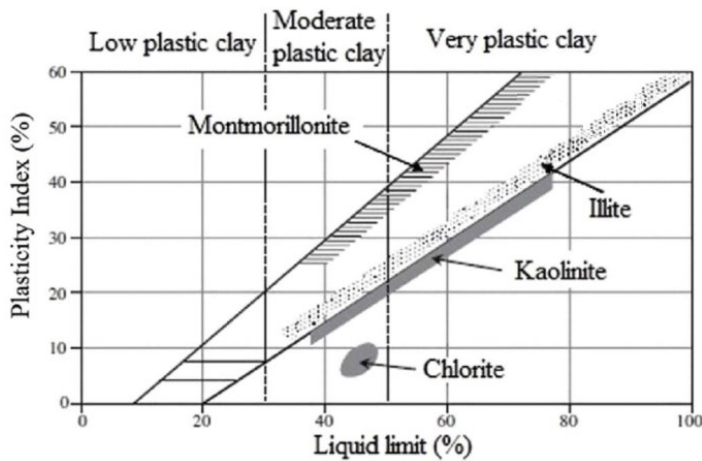


Fig. 2 A clay classification based on Atterberg limits (Holtz & Kovacs, 1981)

The physical properties of clays, including particle size distribution and mineral composition, directly affect their behavior. Fine particle size, for example, contributes to higher specific surface areas, which in turn increase water absorption and plasticity (Žbik et al., 2015). Mechanical properties such as shear strength, tensile strength, and compressive strength are fundamental for understanding how clays respond to stresses. The inter-particle forces and the bonding between clay particles determine their overall strength and stability when subjected to external loads (Noaman et al., 2022). Moisture content plays a significant role in the behavior of clay soils. Variations in water content can lead to changes in volume and strength, which must be carefully considered during the design of foundations, embankments, and retaining structures (Cherif et al., 2018).

Laboratory tests such as consolidation tests, triaxial shear tests, and direct shear tests are essential in evaluating the engineering properties of clays. These tests help in determining the settlement behavior, shear strength parameters, and overall stability of clayey soils under various loading conditions (Holtz & Kovacs, 1981). Understanding the engineering behavior of clays is critical for predicting issues related to slope stability and foundation performance. The variability in clay properties often necessitates the use of specialized construction techniques and soil stabilization measures to mitigate potential risks (Nikbakht et al., 2022). One of the challenges in working with clays is their inherent variability. Even within a single site, clays can exhibit significant differences in properties, making it necessary to adopt a conservative approach in design and to perform thorough site investigations (Ghosh, 2013).

Clay plays a crucial role in agriculture and soil science, with its physical and mechanical properties significantly influencing soil fertility, plant growth, and water retention. From an engineering geology perspective, understanding these properties is essential for land-use planning, irrigation management, and soil conservation. The fine-grained nature of clay particles, their high surface area, and their ability to retain water and nutrients make clay-rich soils both beneficial and challenging in agricultural applications (Haghsheno & Arabani, 2022). One of the most important physical properties of clay is its particle size. Clay particles are the smallest among soil components, with diameters less than 2 microns. This fine particle size results in a high specific surface area, which enhances nutrient and moisture

retention (Tournassat et al., 2015). However, it also leads to poor drainage, making clayey soils prone to waterlogging. In agricultural practices, proper drainage systems and soil amendments, such as organic matter incorporation, are necessary to improve aeration and prevent root suffocation (O'Kelly, 2021).

Water retention capacity is another key factor affecting plant growth. Clay minerals, particularly those in the smectite group, can absorb large amounts of water due to their expansive nature. While this ability helps sustain crops during dry periods, excessive water retention can lead to oversaturation, reducing soil aeration and microbial activity (Zhou & Keeling, 2013). From an engineering geology perspective, managing water balance in clayey soils is critical to prevent compaction, erosion, and instability in farmlands. Soil compaction is a major mechanical challenge associated with clay-rich soils. Due to their cohesive nature, clays are prone to compaction under mechanical pressure, such as from heavy machinery or livestock (Blyth & De Freitas, 2017). Compacted soils have reduced pore spaces, which restricts root penetration, water infiltration, and gas exchange. To mitigate this issue, agricultural engineers recommend deep tillage, controlled traffic farming, and the use of cover crops to maintain soil structure and porosity (Stoltz et al., 2012). The shrink-swell behavior of expansive clays poses another significant challenge in agricultural land management. Clays that contain montmorillonite and other smectitic minerals expand when wet and shrink upon drying, causing cracks and instability in soil beds. This dynamic movement can damage plant roots, disrupt irrigation channels, and lead to uneven crop growth (Soga et al., 2017). Engineering solutions, such as soil stabilization with gypsum or lime, can help reduce the severity of swelling and shrinkage cycles (Stoltz et al., 2012).

Clay mineralogy also plays a vital role in soil fertility. The CEC of clay minerals determines their ability to hold and exchange essential nutrients, such as potassium, calcium, and magnesium. Smectite and vermiculite clays have high CEC values, making them effective at retaining nutrients for plant uptake. However, kaolinite, with its low CEC, requires additional fertilization to maintain soil productivity. Understanding these mineralogical differences helps agronomists and soil scientists optimize fertilizer application and soil amendments (Kome et al., 2019). The pH and chemical composition of clayey soils also influence their agricultural viability. Certain clay types, such as those derived from weathered basaltic rocks, tend to be rich in iron and aluminum oxides, leading to soil acidity (Blyth & De Freitas, 2017). Acidic soils can limit nutrient availability and reduce crop yields. To counteract soil acidity, agricultural engineers often apply lime to increase pH levels and enhance soil fertility (Bahmed et al., 2019). On the other hand, alkaline clay soils may require sulfur-based amendments to improve nutrient solubility (Firoozi et al., 2016).

Salinity issues in clay soils pose another agricultural challenge, particularly in irrigated farmlands. Clay soils with poor drainage can accumulate salts over time, leading to soil degradation and reduced crop yields (Firoozi et al., 2016). The high capillary action of clays can bring dissolved salts to the surface, causing crust formation and hindering seedling emergence. Engineering solutions such as subsurface drainage systems and leaching practices are necessary to manage soil

salinity effectively (Blyth & De Freitas, 2017). Microbial activity and organic matter decomposition are also influenced by clay content. While clay provides a protective environment for soil microbes, excessive compaction and poor aeration can suppress biological activity. Beneficial microbes play a crucial role in nutrient cycling, organic matter decomposition, and disease suppression. To enhance microbial health, organic amendments such as compost or biochar are often added to clayey soils (Tournassat et al., 2015).

Iranian clays present a unique case within the realm of geotechnical engineering due to their distinct geological settings and mineralogical compositions. Distributed widely across various regions of Iran, these clays offer a diverse range of properties that influence construction practices and soil management strategies (Khodami & Shervedani, 2018). The mineralogy of Iranian clays is varied, with many regions exhibiting clays that are rich in kaolinite, illite, and smectite. This diversity in mineral composition leads to differences in plasticity, cohesion, and chemical behavior, which are critical factors in geotechnical assessments (Johari et al., 2021). In terms of Atterberg limits, Iranian clays often display a wide range of liquid and plastic limits, reflecting their heterogeneous nature. Some areas report high plasticity indices that suggest a greater potential for volume changes with moisture variations, while other deposits are relatively more stable (Firoozi et al., 2016).

Compressibility is another important aspect of Iranian clays. Many of these clays have been found to undergo significant consolidation, resulting in noticeable settlement under load. This behavior necessitates careful design and remediation measures, especially in regions prone to seismic activity and heavy construction loads (Momeni et al., 2022). The mechanical behavior of Iranian clays is equally varied. Some clays exhibit high shear strength and low compressibility, making them suitable for foundation support, whereas others, particularly those with higher smectite content, show lower strength and higher susceptibility to deformation (Nikbakht et al., 2022). Physically, Iranian clays often exhibit a fine-grained texture with significant water-holding capacities. This physical characteristic, combined with their chemical composition, can lead to challenges such as swelling and shrinkage, which impact drainage and long-term stability of constructed structures (Khodami & Shervedani, 2018).

The United States Department of Agriculture (USDA) soil classification system is one of the most widely used methods for categorizing soils based on their particle size distribution. In this system, soils are classified into sand, silt, and clay based on the percentage of each component (Zhu et al., 2019). Clay is defined as any soil particle with a diameter of less than 2 microns. Unlike other classification systems that focus on mineralogical composition, the USDA system (Figure 3) primarily emphasizes particle size, making it a useful tool for agricultural, engineering, and environmental applications (Blyth & De Freitas, 2017). The USDA soil texture triangle is used to determine soil types based on the proportions of sand, silt, and clay (Cherif et al., 2018). Clay soils, according to this system, contain at least 40% clay, less than 45% sand, and less than 40% silt. These soils are further categorized into different textural classes, such as clay, sandy clay, silty clay, and clay loam, each with distinct physical and chemical properties (Holtz & Kovacs, 1981).

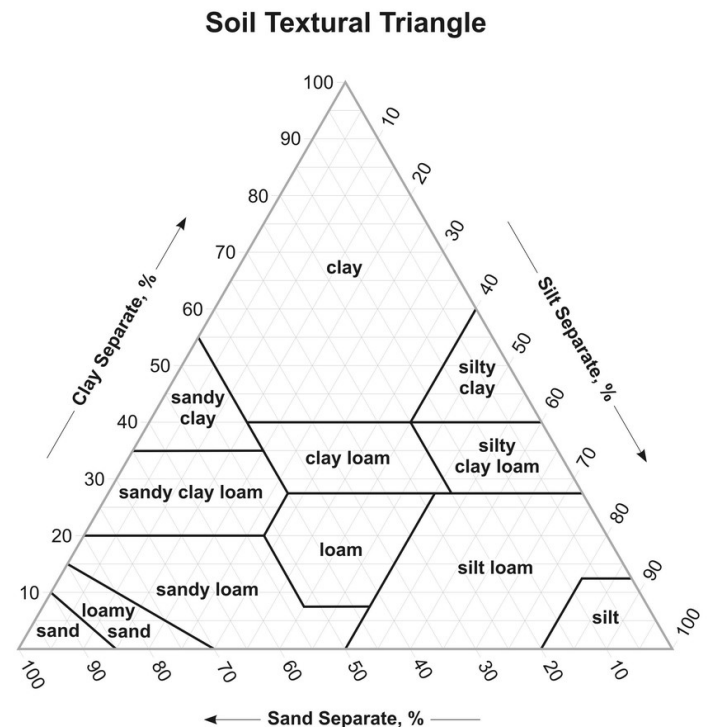


Fig. 3 USDA soil classification chart (Tu & LeBauer, 2011)

The classification helps in understanding soil behavior, including water retention, permeability, and fertility, which are essential factors in agriculture, construction, and geotechnical engineering (Tu & LeBauer, 2011). One of the major advantages of the USDA classification system is its applicability in soil management and land-use planning. For instance, clay soils with high water retention and low permeability require proper drainage techniques to prevent waterlogging in agricultural fields. Similarly, clayey soils with high shrink-swell potential must be considered in geotechnical projects to avoid structural damage (Abdelfattah & Shahid, 2007). The system also aids in determining erosion risks, irrigation suitability, and nutrient availability, making it an essential tool for farmers, soil scientists, and engineers (Moreno-Maroto & Alonso-Azcarate, 2022).

In Iran, the USDA soil classification system is widely recognized and applied in agriculture, soil science, and engineering geology. Many Iranian research institutions, universities, and government agencies use this method for soil surveys, land evaluation, and environmental assessments. The classification system helps Iranian soil scientists categorize the country's diverse soils, ranging from the loamy soils of the Caspian region to the clay-rich arid soils of central and southeastern Iran. Additionally, Iranian farmers and agronomists rely on USDA-based classifications to develop proper irrigation and soil amendment strategies for improving agricultural productivity. Despite its advantages, the USDA system has some limitations, particularly in regions like Iran, where soil mineralogy and chemical composition significantly influence soil behavior. While the USDA method focuses on particle size, other classification systems, such as the Unified Soil Classification System (USCS) and the FAO/WRB system, consider mineral content, soil genesis, and chemical properties. As a result, Iranian experts often integrate multiple classification approaches to

obtain a more comprehensive understanding of soil properties for various applications, including agriculture, geotechnical engineering, and environmental sustainability.

IV. CONCLUSION

The physical properties of clayey soils play a crucial role in shaping agricultural strategies, influencing water retention, drainage, nutrient availability, and soil aeration. The USDA soil classification system, which categorizes soils based on particle size, is widely used to identify clay-rich soils and assess their suitability for different agricultural practices. Clayey soils, defined as having at least 40% clay, exhibit high water-holding capacity, low permeability, and significant plasticity, making them beneficial for certain crops while posing challenges for others. One of the key factors in managing clayey soils is addressing their water retention and drainage characteristics. While these soils can hold large amounts of moisture, excessive water retention may lead to waterlogging, which negatively impacts root development and microbial activity. To counter this, proper irrigation management, soil aeration techniques, and organic matter amendments are essential for optimizing agricultural productivity. In addition, the shrink-swell behavior of expansive clay soils must be considered when designing sustainable agricultural infrastructure such as irrigation canals and greenhouses. The USDA soil classification system is extensively used in Iran for soil evaluation and land-use planning. Given the diverse soil conditions across the country, from the fertile northern plains to the arid central deserts, understanding the physical and mechanical properties of clay helps in developing appropriate soil management strategies. By integrating USDA classification with local soil assessments, Iranian farmers and agricultural experts can implement site-specific solutions to improve crop yields, prevent erosion, and enhance soil fertility. In conclusion, the physical properties of clayey soils are fundamental in determining effective agricultural practices. With proper classification, soil amendments, and water management techniques, these soils can be optimized for sustainable farming, ensuring long-term agricultural productivity and environmental conservation.

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AUTHORS' CONTRIBUTIONS

Moharam Fatemi and Sajad Alizade conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and were responsible for drafting the initial manuscript. Mohammad Gorbani performed supervision, conceptual guidance, and critical revision of the manuscript. Sajad Alizade provided overall project administration and final approval of the version to be published. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors have not disclosed any competing interests.

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REFERENCES

- Abdelfattah M.A., Shahid S.A. (2007). A comparative characterization and classification of soils in Abu Dhabi coastal area in relation to arid and semi-arid conditions using USDA and FAO soil classification systems. *Arid Land Research and Management*, 21(3), 245-271. <https://doi.org/10.1080/15324980701426314>.
- Adeyanju E.A., Okeke C.A. (2019). Clay soil stabilization using cement kiln dust. *IOP Conference Series: Materials Science and Engineering*, 640(1), 012080. <https://doi.org/10.1088/1757-899X/640/1/012080>.
- Ahmed S.M., Agaiby S.S. (2020). Strength and stiffness characterization of clays using Atterberg limits. *Transportation Geotechnics*, 25, 100420. <https://doi.org/10.1016/j.trgeo.2020.100420>.
- Amri S., Akkiche M., Bennabi A., Hamzaoui R. (2019). Geotechnical and mineralogical properties of treated clayey soil with dune sand. *Journal of African Earth Sciences*, 152, 140-150. <https://doi.org/10.1016/j.jafrearsci.2019.01.010>.
- Anikwe M.A.N. (2000). Amelioration of a heavy clay loam soil with rice husk dust and its effect on soil physical properties and maize yield. *Bioresource Technology*, 74(2), 169-173. [https://doi.org/10.1016/S0960-8524\(00\)00007-9](https://doi.org/10.1016/S0960-8524(00)00007-9).
- Bahmed I.T., Harichane K., Ghrici M., Boukhatem B., Rebouh R., Gadouri H. (2019). Prediction of geotechnical properties of clayey soils stabilised with lime using artificial neural networks (ANNs). *International Journal of Geotechnical Engineering*, 13(2), 191-203. <https://doi.org/10.1080/19386362.2017.1329966>.
- Baldovino J.A., Moreira E.B., Teixeira W., Izzo R.L., Rose J.L. (2018). Effects of lime addition on geotechnical properties of sedimentary soil in Curitiba, Brazil. *Journal of Rock Mechanics and Geotechnical Engineering*, 10(1), 188-194. <https://doi.org/10.1016/j.jrmge.2017.10.001>.
- Bergaya F., Lagaly G. (2006). General introduction: clays, clay minerals, and clay science. *Developments in Clay Science*, 1, 1-18. [https://doi.org/10.1016/S1572-4352\(05\)01001-9](https://doi.org/10.1016/S1572-4352(05)01001-9).
- Blyth F.G.H., De Freitas M. (2017). *A Geology for Engineers*. CRC Press, Florida, USA.
- Cherif M.M., Amal M., Ramdane B. (2018). Effect of swelling mineral on geotechnical characteristics of clay soil. In: *Proceedings of the MATEC Web of Conferences*, 149, 02067. <https://doi.org/10.1051/mateconf/201814902067>.
- Dhar S., Hussain M. (2019). The strength behaviour of lime-stabilised plastic fibre-reinforced clayey soil. *Road Materials and Pavement Design*, 20(8), 1757-1778. <https://doi.org/10.1080/14680629.2018.1468803>.
- Do Nascimento G. (2021). *Clay and Clay Minerals*. intechopen press, London, UK.
- Firoozi A.A., Firoozi A.A., Baghini M.S. (2016). A review of clayey soils. *Asian Journal of Applied Sciences*, 4(06), 1319-1330.
- Ghosh B., Chakraborty D. (2023). *Clay Minerals: Their Antimicrobial and Antitoxic Applications*. Springer, Cham, Switzerland.
- Ghosh R. (2013). Effect of soil moisture in the analysis of undrained shear strength of compacted clayey soil. *Journal of Civil Engineering and Construction Technology*, 4(1), 23-31. <https://doi.org/10.5897/JCECT12.070>.

- Gillott J.E. (2012). *Clay in Engineering Geology*. Elsevier, Amsterdam, The Netherlands.
- GuhaRay A., Guoxiong M., Sarkar A., Bordoloi S., Garg A., Pattanayak S. (2019). Geotechnical and chemical characterization of expansive clayey soil amended by biochar derived from invasive weed species *Prosopis juliflora*. *Innovative Infrastructure Solutions*, 4, 1-10. <https://doi.org/10.1007/s41062-019-0231-2>.
- Haghsheeno H., Arabani M. (2022). Geotechnical properties of oil-polluted soil: a review. *Environmental Science and Pollution Research*, 29(22), 32670-32701. <https://doi.org/10.1007/s11356-022-19418-1>.
- Hajdarwish A., Shakoor A., Wells N.A. (2013). Investigating statistical relationships among clay mineralogy, index engineering properties, and shear strength parameters of mudrocks. *Engineering Geology*, 159, 45-58. <https://doi.org/10.1016/j.enggeo.2013.03.016>.
- Hassan H.J.A., Rasul J., Samin M. (2021). Effects of plastic waste materials on geotechnical properties of clayey soil. *Transportation Infrastructure Geotechnology*, 8(3), 390-413. <https://doi.org/10.1007/s40515-020-00145-4>.
- Holtz R.D., Kovacs W.D. (1981). *An Introduction to Geotechnical Engineering*. Prentice Hall, New Jersey, USA.
- Johari A., Golkarfard H., Davoudi F., Fazeli A. (2021). A predictive model based on the experimental investigation of collapsible soil treatment using nano-clay in the Sivand Dam region, Iran. *Bulletin of Engineering Geology and the Environment*, 80, 6725-6748. <https://doi.org/10.1007/s10064-021-02360-w>.
- Karkush M.O., Ali S.D. (2020). Impacts of lead nitrate contamination on the geotechnical properties of clayey soil. *Journal of Engineering Science and Technology*, 15(2), 1032-1045.
- Karkush M.O., Yassin S.A. (2020). Using sustainable material in improvement the geotechnical properties of soft clayey soil. *Journal of Engineering Science and Technology*, 15(4), 2208-2222.
- Karpiński B., Szkodo M. (2015). Clay minerals—mineralogy and phenomenon of clay swelling in oil & gas industry. *Advances in Materials Science*, 15(1), 37-55. <https://doi.org/10.1515/adms-2015-0006>.
- Khodami M., Shervedani A.K. (2018). Mineralogical and geochemical characteristics of the Chah-Shur clay deposit, Southeast of Isfahan, Iran. *Iranian Journal of Earth Sciences*, 10(1), 135-141.
- Klimov S.V., Klimova A.V. (2022). Drainage reconstruction in the zone of excessive moisture during the cultivation of blueberries on poorly water-permeable clay soils. *IOP Conference Series: Earth and Environmental Science*, 1049(1), 012038. <https://doi.org/10.1088/1755-1315/1049/1/012038>.
- Kome G.K., Enang R.K., Tabi F.O., Yerima B.P.K. (2019). Influence of clay minerals on some soil fertility attributes: a review. *Open Journal of Soil Science*, 9(9), 155-188. <https://doi.org/10.4236/ojss.2019.99010>.
- Lu S.G., Sun F.F., Zong Y.T. (2014). Effect of rice husk biochar and coal fly ash on some physical properties of expansive clayey soil (Vertisol). *Catena*, 114, 37-44. <https://doi.org/10.1016/j.catena.2013.10.014>.
- Mohammed A.S. (2018). Property correlations and statistical variations in the geotechnical properties of (CH) clay soils. *Geotechnical and Geological Engineering*, 36, 267-281. <https://doi.org/10.1007/s10706-017-0325-6>.
- Momeni M., Bayat M., Ajalloeian R. (2022). Laboratory investigation on the effects of pH-induced changes on geotechnical characteristics of clay soil. *Geomechanics and Geoengineering*, 17(1), 188-196. <https://doi.org/10.1080/17486025.2020.1716084>.
- Moreno-Maroto J.M., Alonso-Azcarate J. (2022). Evaluation of the USDA soil texture triangle through Atterberg limits and an alternative classification system. *Applied Clay Science*, 229, 106689. <https://doi.org/10.1016/j.clay.2022.106689>.
- Nikbakht M., Sarand F.B., Irani A.E., Bonab M.H., Azarafza M., Derakhshani R. (2022). An experimental study for swelling effect on repairing of cracks in fine-grained clayey soils. *Applied Sciences*, 12(17), 8596. <https://doi.org/10.3390/app12178596>.
- Noaman M.F., Khan M.A., Ali K., Hassan A. (2022). A review on the effect of fly ash on the geotechnical properties and stability of soil. *Cleaner Materials*, 6, 100151. <https://doi.org/10.1016/j.clema.2022.100151>.
- O'Kelly B.C. (2021). Review of recent developments and understanding of Atterberg limits determinations. *Geotechnics*, 1(1), 59-75. <https://doi.org/10.3390/geotechnics1010004>.
- Ojuri O.O., Ramdas V., Aderibigbe E.A., Williams C.G., Ramchuran S., Al-Nageim H. (2022). Improving strength and hydraulic characteristics of regional clayey soils using biopolymers. *Case Studies in Construction Materials*, 17, e01319. <https://doi.org/10.1016/j.cscm.2022.e01319>.
- Phogat V.K., Tomar V.S., Dahiya R. (2015). Soil physical properties. *Soil science: An introduction*, pp. 135-171.
- Pushpakumara B.H.J., Mendis W.S.W. (2022). Suitability of Rice Husk Ash (RHA) with lime as a soil stabilizer in geotechnical applications. *International Journal of Geo-Engineering*, 13(1), 4. <https://doi.org/10.1186/s40703-021-00169-w>.
- Rahgozar M.A., Saberian M., Li J. (2018). Soil stabilization with non-conventional eco-friendly agricultural waste materials: An experimental study. *Transportation Geotechnics*, 14, 52-60. <https://doi.org/10.1016/j.trgeo.2017.09.004>.
- Sharma A., Sharma R.K. (2021). Sub-grade characteristics of soil stabilized with agricultural waste, constructional waste, and lime. *Bulletin of Engineering Geology and the Environment*, 80(3), 2473-2484. <https://doi.org/10.1007/s10064-020-02047-8>.
- Soga K., Laver R.G., Li Z. (2017). Long-term tunnel behaviour and ground movements after tunnelling in clayey soils. *Underground Space*, 2(3), 149-167. <https://doi.org/10.1016/j.undsp.2017.08.001>.
- Stoltz G., Cuisinier O., Masroufi F. (2012). Multi-scale analysis of the swelling and shrinkage of a lime-treated expansive clayey soil. *Applied Clay Science*, 61, 44-51. <https://doi.org/10.1016/j.clay.2012.04.001>.
- Tarback E., Lutgens F., Tasa D. (2016). *Earth: An Introduction to Physical Geology (12th edition)*. Pearson, London, England.
- Taser O.F., Metinoglu F. (2005). Physical and mechanical properties of a clayey soil as affected by tillage systems for wheat growth. *Acta Agriculturae Scandinavica Section B-soil and Plant*, 55(3), 186-191. <https://doi.org/10.1080/09064710510008702>.
- Tournassat C., Bourg I.C., Steefel C.I., Bergaya F. (2015). Surface properties of clay minerals. *Developments in Clay Science*, 6, 5-31. <https://doi.org/10.1016/B978-0-08-100027-4.00001-2>.
- Tu A., LeBauer D. (2011). *Data Entry Workflow for the Biofuel Ecophysiological Traits and Yields Database (BETydb)*. Available at: <https://shorturl.at/LV7Xs> [Accessed on March 2025].
- Varghese R., K.R. (2021). Geotechnical behaviour of different organic matter on clayey soils. *Geomechanics and Geoengineering*, 16(4), 288-297. <https://doi.org/10.1080/17486025.2019.1670874>.
- Velde B. (1992). *Introduction to Clay Minerals: Chemistry, origins, uses and environmental significance*. Springer, Cham, Switzerland.
- Žbik M.S., Williams D.J., Song Y.F., Wang C.C. (2015). Smectite clay microstructural behaviour on the Atterberg limits transition. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 467, 89-96. <https://doi.org/10.1016/j.colsurfa.2014.11.042>.
- Zhou C.H., Keeling J. (2013). Fundamental and applied research on clay minerals: From climate and environment to nanotechnology. *Applied Clay Science*, 74, 3-9. <https://doi.org/10.1016/j.clay.2013.02.013>.
- Zhu F., Li Z., Dong W., Ou Y. (2019). Geotechnical properties and microstructure of lime-stabilized silt clay. *Bulletin of Engineering Geology and the Environment*, 78, 2345-2354. <https://doi.org/10.1007/s10064-018-1307-5>.