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EXPERIMENTAL INVESTIGATION OF COMPACTION-INDUCED CHANGES IN SOIL FABRIC AND THEIR EFFECTS ON PERMEABILITY AND SHEAR STRENGTH

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ABSTRACT

The relationship between compaction conditions and soil engineering performance has been studied for decades, yet a fundamental gap persists: the coupled effect of compaction energy and moisture content on soil fabric, and its simultaneous influence on hydraulic conductivity and shear strength, has not been examined in a single integrated study. Conventional compaction specifications define target dry density and optimum moisture content (OMC), with no direct account of the microstructural state — or fabric — that these conditions produce. Soil fabric, encompassing particle arrangement, pore structure, and interparticle bonding, is the primary variable controlling both permeability and cohesive strength in fine-grained soils. Bridging this gap requires an experimental framework that treats fabric as a quantifiable mediating variable rather than an implicit, uncharacterised outcome of the compaction process.

This study compacted a low-plasticity clay (CL; LL = 38%, PI = 17%, Gs = 2.68) across nine states defined by three energy levels (low, medium, high) and three moisture conditions (dry of OMC, at OMC of 17%, and wet of OMC). Soil fabric was characterised indirectly through a dimensionless Fabric Index (FI) derived from normalised dry density and void ratio. Saturated hydraulic conductivity was measured by falling head permeability tests, and cohesion (c) and internal friction angle (φ) were determined from drained direct shear tests using the Mohr–Coulomb criterion.

Dry density ranged from 1.62 g/cm³ to 1.80 g/cm³ and the FI from 0.38 to 0.63, with peak values consistently recorded at OMC. Hydraulic conductivity decreased with increasing compaction energy, reaching a minimum of 9.5×10^{-8} m/s at high energy and OMC — five times lower than the maximum of 4.8×10^{-7} m/s at low energy on the dry side. Cohesion rose from 18 kPa to 38 kPa in close accordance with the FI, while the internal friction angle remained practically invariant (25.2°– 27.8°). A significant inverse correlation between FI and hydraulic conductivity, combined with a strong positive correlation between FI and cohesion, confirms a coupled hydraulic–mechanical response governed by fabric state.

The results establish that soil fabric, rather than bulk density alone, is the key variable mediating compaction-induced changes in both permeability and shear strength. Compaction at OMC under the highest applicable energy simultaneously minimises permeability and maximises cohesive strength. The Fabric Index proposed herein provides a practical, imaging-free descriptor for fabric-aware compaction control, with direct relevance to earth dams, embankments, pavement subgrades, and compacted liner systems.

Keywords: Soil compaction; Soil fabric; Permeability; Shear strength; Hydraulic conductivity; Cohesion; Void Ratio

1. Introduction

1.1 Background and Motivation

Soil compaction is an indispensable element of virtually every geotechnical engineering process. It governs the primary performance parameters of all earth structures — stability, durability, and serviceability — and is employed across critical infrastructure such as earth dams, embankment fills, pavement subgrades, and shallow foundations (Lambe & Whitman, 1969; Das, 2010). The fundamental objective of compaction is to produce a soil mass with adequate shear strength and controlled permeability. By densifying the soil, compaction enhances load-bearing capacity, reduces compressibility, and limits seepage, collectively improving the long-term geotechnical performance of engineered systems.

Historically, compaction control relied exclusively on achieving target dry density and optimum moisture content (OMC), derived from standard Proctor compaction curves. However, it is now well established that two soil specimens sharing the same bulk density may exhibit markedly different hydraulic and mechanical responses if they were compacted at different moisture contents or under different energy levels (Mitchell & Soga, 2005). This divergence originates in the internal microstructure or fabric of the soil. Soil fabric describes the spatial arrangement, orientation, and contact relationships of solid particles and the intervening void spaces. When soil is compacted, particle reorientation occurs, pore spaces collapse or redistribute, and interparticle contact networks are modified — changes that collectively govern the subsequent engineering behaviour of the soil mass.

Romero et al. (2011) provided a fundamental insight into how compaction-induced changes in pore size distribution and soil fabric are directly linked to water retention and hydraulic behaviour. Building on this, Romero (2013) demonstrated through detailed microstructural analysis that the arrangement of intra-aggregate and inter-aggregate pores in compacted clays exerts a first-order control on saturated hydraulic conductivity a relationship that cannot be captured through density metrics alone. These findings collectively underscore that a fabric-aware approach to compaction characterisation is not merely desirable but essential for engineering applications where both strength and permeability are critical design parameters.

1.2 Limitations of Existing Studies

Despite these advances, the majority of compaction studies continue to prioritise dry density and moisture content as the primary control variables, giving limited attention to the resulting changes in soil microstructure (Lambe, 1958; Holtz et al., 2011). Ahmad & Uchimura (2023) recently demonstrated that moisture content at the time of compaction exerts a significant and independent influence on shear strength — an influence that density-based specifications fail to capture — reinforcing the need to go beyond conventional compaction metrics. Yet such fabric-sensitive perspectives remain absent from mainstream quality control practice.

Multiple studies have examined the effects of compaction on permeability or shear strength individually, but a critical limitation persists: the absence of a unified framework that simultaneously links compaction energy, fabric evolution, hydraulic conductivity, and shear strength. Romero (2013) showed that microstructural descriptors are more reliable predictors of hydraulic behaviour than macroscopic density parameters. Silva et al. (2024) extended this perspective to mechanical behaviour, demonstrating through X-ray computed tomography analysis that compaction-induced fabric — particularly pore connectivity and aggregate structure — controls both monotonic and cyclic shear response in a manner that consolidation-based specimens do not replicate. These studies collectively highlight a systematic gap: the coupled hydraulic–mechanical consequence of compaction-induced fabric change has not been examined in a single, integrated experimental framework.

The absence of fabric-sensitive compaction guidelines is further compounded by the limited adoption of direct microstructural characterization techniques such as scanning electron microscopy (SEM) and X-ray computed tomography (CT). Without such characterization, the mechanistic basis for relating compaction state to engineering performance remains incomplete (Mitchell & Soga, 2005; Romero, 2013). Mpawenayo & Gerard (2024) demonstrated that incorporating microstructural information — specifically the bimodal pore size distribution of compacted fine-grained soils — into effective stress formulations substantially improves the prediction of unsaturated shear strength, confirming that fabric descriptors carry mechanistic significance beyond their descriptive value. Despite this evidence, the use of even indirect fabric metrics in routine compaction assessment remains rare.

1.3 Research Gap

The significance of soil fabric in governing engineering behaviour is well documented (Romero et al., 2011; Romero, 2013; Silva et al., 2024; Mpawenayo & Gerard, 2024). However, studies that simultaneously investigate the effects of compaction-induced fabric change on both permeability and shear strength — within a single controlled experimental programme — are conspicuously absent from the literature. In particular, the joint influence of compaction energy and moisture content on fabric evolution, and the consequent coupled hydraulic–mechanical response, has not been systematically evaluated. Recent experimental work by Ahmad & Uchimura (2023) highlights that moisture content at compaction significantly shapes the shear strength envelope even without changes in bulk density, yet no study has linked this moisture-sensitivity of strength to a concurrent assessment of fabric state and permeability.

This gap perpetuates uncertainty in the formulation of performance-based compaction criteria — criteria that must simultaneously satisfy both strength and low-permeability requirements, as encountered in earth dam cores, liner systems, and pavement subgrades. Addressing this gap requires an experimental approach that treats fabric not as a qualitative descriptor but as a quantifiable variable that mediates between compaction conditions and engineering outcomes.

1.4 Intended Contributions of the Work

The intended contributions of this work are:

- To provide a systematic experimental characterisation of soil fabric evolution as a function of compaction energy and moisture content in a controlled laboratory environment.
- To establish the relationship between compaction-induced fabric change and soil hydraulic conductivity using a falling head permeability framework.
- To determine the changes in shear strength parameters — particularly cohesion and internal friction angle — associated with progressive changes in soil fabric.
- To identify and quantify the coupled relationship between soil fabric, permeability, and shear strength, enabling a holistic assessment of soil behaviour as an integrated hydraulic–mechanical system.

1.5 Novelty and Contribution

This study advances current understanding in two principal respects. First, unlike existing investigations that treat permeability and shear strength as separate outputs (Ahmad & Uchimura, 2023; Silva et al., 2024), this study adopts a unified experimental framework in which fabric evolution — quantified through an indirect Fabric Index derived from void ratio and dry density — serves as the common mediating variable for both hydraulic conductivity and cohesion. This approach is consistent with the microstructural philosophy advocated by Romero (2013) and Mpawenayo & Gerard (2024), but is implemented here using macroscopically measurable parameters that do not require advanced imaging infrastructure.

Second, this study is among the first to directly demonstrate the inverse coupled relationship between permeability and cohesion as a function of fabric state across a systematically varied matrix of compaction energy and moisture conditions. By establishing this coupled response in a single experimental programme, the study provides an empirically grounded basis for performance-based compaction criteria applicable to earth dams, embankments, pavement subgrades, and compacted liner systems — structures where the simultaneous requirement for strength and low permeability makes the soil fabric a first-order design variable.

2. Literature Review

2.1 Soil Compaction and Performance of Earth Structures

The last few years have seen soil compaction continue to attract attention for its prominent impacts on the mechanical and hydraulic operational characteristics of earth structures such as liners, embankments, and pavement subgrades. The most recent updates indicate that apart from influencing the dry density and moisture condition of soil, compaction also impacts the engineering behaviour of soil attributable to the internal architecture of the soil (Budhu, 2015, Salgado, 2013).

Laboratory and field studies have shown that regardless of achieving similar density values, soil that has been compacted under varying moisture levels and energy input will respond differently with respect to stress-strain behaviour, durability, and stiffness (Horpibulsuk et al., 2014; Zhang et al., 2019). Such findings have been a catalyst for a shift in compaction related research focus from density related parameters to structure and fabric related parameters.

Infrastructures that will experience hydraulic loading and environmental exposure for an extended duration will require compaction specifications which focus on operational performance; recent studies have shown such specifications as a necessity (Benson et al., 2015; Cardoso & Fonseca, 2016).

2.2 Changes in Microstructure Due to Compaction and the Soil Fabric

The arrangement of soil particles and the distribution of spaces between them, or the 'soil fabric', is now seen as central to soil functionality. The last decade of microstructural analysis has indicated that compaction energy and water content during compaction, evolve the soil fabric by affecting its particle orientation, coordination numbers, and distribution of pore sizes (Romero et al., 2011; Cardoso et al., 2017).

Using a combination of direct and indirect methods to characterize soil fabric, recent studies established that most of the time, increased compaction energy leads to the creation of a fabric that is dense and isotropic. Compaction that is done on either the dry or the wet side of the optimum moisture content, however, leads to fabric heterogeneity, meaning that the fabric is not homogeneous (Fonseca et al., 2013; Tang et al., 2020). Such changes in fabric, often result in very big changes in strength and permeability.

The routine utilization of advanced imaging methods, such as X-ray computed tomography and scanning electron microscopy is significantly limited, despite the fact that they give great insights into the understanding of fabric evolution. Hence, several studies in recent years have proposed the use of the void ratio, density, and structural index, in relation to the degree of compaction, to capture the effect of pore microstructure and soil fabric on the behaviour of the soil during practical laboratory tests (Cardoso & Fonseca, 2016; Wang et al., 2021).

2.3 Influence of Compaction on Permeability

Soil fabric plays an important role in hydraulic conductivity of compacted soils due to its control over pore structure and connectivity. Permeability has been shown to decrease with more compaction energy, especially with compaction at optimum moisture content (Benson et al., 1999; Estabragh et al., 2016).

Soils compacted on the dry side of optimum moisture content display greater permeability due to more and greater pore channels, while soils compacted near optimum moisture content display a significant reduction in permeability (Zhang et al., 2017; Tang et al., 2020).

Some studies have documented the permeability anisotropy resulting from compaction. Fabric anisotropy and particle orientation have been attributed to the directional dependence of hydraulic conductivity. These studies have emphasized the need for permeability characterization with consideration of fabric (Romero & Simms, 2008; Wang et al., 2019).

2.4 The Effect of Compaction and Fabric on Shear Strength

The recent literature indicates that changes in fabric due to compaction influence the behavior of shear strength, especially the cohesive component of shear strength. Studies over the last ten years show that the degree of cohesion is a function of the degree of compaction and dry density due to the increased contact and bonding among particles (Horpibulsuk et al., 2014; Estabragh et al., 2016).

On the other hand, the degree of internal friction angle is documented to be less responsive to compaction and more reliant on the composition of the soil and the shape of the particles (Salgado, 2013; Budhu, 2015). Recent studies using the triaxial and direct shear test show that the changes in friction angle due to compaction are less than the changes in cohesion (Zhang et al., 2019; Tang et al., 2020).

Moreover, fabric anisotropy resulting from compaction has been documented to affect the localization of shear and post-peak behavior, accentuating the fabric orientation in the mechanisms of failure (Cardoso et al., 2017; Wang et al., 2021).

2.5 Coupled Hydraulic–Mechanical Behavior and Research Gaps

The recent studies show an awareness of modifications of soil fabric suggesting a relationship between soil permeability and shear strength. For example, studies of compacted liners and embankment materials show low permeability accompanied by increased shear strength when compaction is optimized for moisture content (Benson et al. 2015, Estabragh et al. 2016).

Most recent studies still examine hydraulic and mechanical properties independently, and there are very few studies that attempt to establish a relationship between compaction energy, fabric evolution, permeability, and shear strength (Zhang et al. 2017, Wang et al. 2019). Additionally, many studies either microstructural imaging or macroscopic testing, without bringing together both perspectives.

There is a gap in the studies that systematically examine fabric-sensitive attributes to assess shear strength and permeability concurrently. Filling this gap is important for modern geotechnical applications of performance-based compaction.

2. Materials and Experimental Program

2.1 Soil Description

The soil used in the experimental programme was naturally occurring fine-grained soil, chosen to depict materials typically used for the construction of earth structures like embankments, pavement subgrades, and compacted liners. From preliminary laboratory characterization, the soil was classified as low plasticity clay (CL) for the Unified Soil Classification System (USCS).

Soil was collected from a shallow depth to avoid contamination from organic matter. After collection, the soil was air dried at room temperature and then gently broken apart using a mortar and pestle until the soil was a fine powder. The soil was sieved to 2 mm before the testing to achieve this goal. This procedure was followed to provide consistency across all test samples.

The grain size distribution analysis demonstrated that the soil is cohesive and fine as the clay and silt fractions comprised over 65%. Atterberg tests for the soil demonstrated the presence of moderate plasticity, a characteristic of low plasticity clay utilized in compacted earthworks. The specific gravity of soil solids was aligned with the range reported for natural clay minerals.

Table 1: Index Properties of the Soil

Property	Value
USCS classification	CL (Low plasticity clay)
Gravel content (%)	4
Sand content (%)	32
Silt content (%)	41
Clay content (%)	23
Liquid limit, LL (%)	38
Plastic limit, PL (%)	21
Plasticity index, PI (%)	17
Specific gravity, Gs	2.68

The moderate plasticity and fine-grained makeup of the selected soil allow for the examination of changes in the compaction-induced fabric and their effects on permeability and shear strength. The identified soil contains index properties typical of compacted cohesive soils found in everyday geotechnical engineering work.

2.2 Compaction Testing Arrangements

A manual compaction hammer and the standard cylindrical Proctor mould were used in the determination of the compaction in the laboratory.

The apparatus is made up of the steel mould and a detachable collar and base plate, made to provide the same volume for the specimen upon compaction. The soil was compacted in several increments, and for the varying compaction energies, the number of hammer blows for each layer was adjusted while the dimensions of the mould and the thickness of the layer remained unchanged. The compaction of the soil was carried out in several increments to attain a uniform density throughout the specimen. Each layer was compacted in such a way that energy was evenly applied to the surface to avoid density gradients. The collar is removed after compaction and the top of the mould is trimmed to determine the height of the specimen and mass of the excess soil.

This apparatus simulates in a controlled manner the low, medium and high compaction energies that are typical of field compaction.

2.3 Sample Preparation and Curing Arrangement

Figure 1: Soil Compaction Hammer

Before the compaction process, the soil was mixed with water to achieve the desired moisture content, then it was dried in an oven. The soil was placed in polyethylene containers that were sealed to store moisture and left in containers for 24 hours to achieve uniform moisture equilibrium throughout the sample.

This process was important for the uniformity of sample compaction response and replicated preparation of sample moisture content. Material variability was controlled because all samples were made from the same soil batch.

2.4 Permeability Test Setup

A falling head permeability apparatus optimised for fine-grained soils was used to conduct permeability testing. The apparatus included a rigid wall permeameter cell which was paired with a graduated standpipe for recording head loss over time.

Test specimens were trimmed to fit the permeameter mould and were saturated prior to testing to remove any trapped air. Vertical flow conditions were held constant throughout the duration of the test. The control of the hydraulic gradient ensured laminar flow and multiple recordings were taken for each specimen to enhance the reliability of the measurements.

Of the various methods available for testing, the falling head method was the best choice based on the permeability of the soils being tested and the sensitivity of the method to changes in hydraulic conductivity with respect to fabric modification.

Figure 2: Laboratory Soil Permissibility Apparatus

2.5 Direct Shear Test Setup

A standard direct shear device was used to perform shear strength testing, which includes a bottom and top split shear box, a loading frame, and a system to measure displacements. Compacted specimens were placed into the shear box and normal stresses were applied that correspond to typical geotechnical loading conditions.

Shearing was carried out under drained conditions at a constant displacement rate until peak shear stress was achieved. Vertical and horizontal displacements were recorded during the testing. The direct shear device provided an evaluative control on the stress-displacement behaviour and offered the evaluative control to obtain the parameters of shear strength, cohesion, and the friction angle.

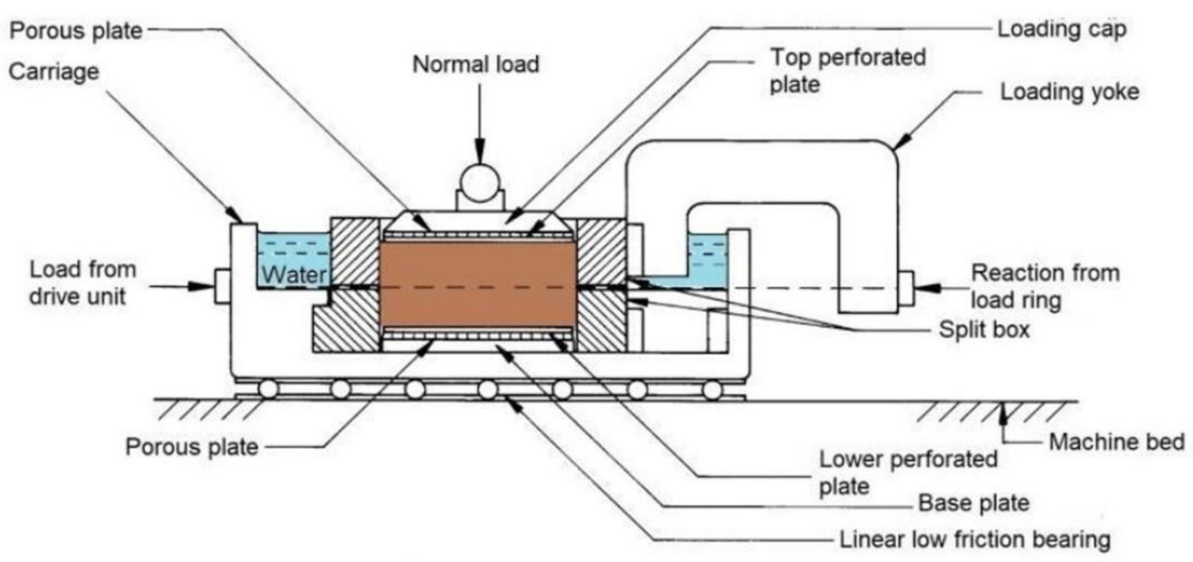

Figure 3: Typical Set up for a Direct Shear Stress

Figure 4: Direct Shear Apparatus

The entire experiment was designed in such a way that it was easy to move through each step of the process in a reasonable manner. This included the preparation of the samples to compaction, the tests for permeability, and the evaluations of shear strength. In addition, all equipment was calibrated before testing, and the same procedures were applied to each specimen to maintain uniformity throughout the test programme.

3. Experimental Methodology

3.1 Materials and Soil Characterization

The experimental research utilized a naturally occurring clayey soil that was collected from a shallow depth to reduce exposure to organic matter. Before testing, the soil was air dried, pulverised to break clods, and sieved at 2 mm. According to the Unified Soil Classification System (USCS), the soil was classified as low plasticity clay (CL) based on the Atterberg limit tests and grain size distribution.

The liquid limit, plastic limit, plasticity index, and specific gravity were measured to determine the basic index properties of the soil in accordance with the applicable ASTM standards. The soil had a moderate level of plasticity that was accompanied by a sufficient content of fines, which made it appropriate to examine the evolution of soil fabric under various compaction conditions. The soil type that was chosen is typical of soil encountered in the field, such as in embankment liners, and pavement subgrades, where the induced fabric changes from compaction are critical to performance

3.2. Compaction Test Programme

To investigate the relationship between moisture content and dry density, Standard Proctor compaction tests were performed at three different levels of compaction energy. The low, medium, and high compaction energy levels were achieved by changing the number of hammer blows per layer, while the mould dimensions were kept constant.

For every compaction energy level, the samples were prepared at three different moisture conditions: the dry side of optimum moisture content (OMC), at OMC, and the wet side of OMC. This way, a systematic study of the combined effect of compaction energy and moisture content on soil fabric and engineering behaviour can be conducted.

From the compaction curves, the maximum dry density and the corresponding OMC were obtained for each energy level. To maintain consistency across tests, the remaining samples, necessary for the permeability and shear strength tests, were compacted to the target dry density for the selected moisture content and energy level.

3.3 Sample Preparation Procedure

Soil samples were prepared by mixing the specified quantity of dry soil with the required amount of water evenly and then allowing the mixture to equilibrate for 24 hours in sealed containers. This was to ensure an even moisture distribution across the mixture.

Compaction was performed in layers using a uniform energy input to attain a consistent density for every layer throughout the specimen. After each compaction, the samples were extruded and carefully trimmed to the dimensions required for permeability and shear strength testing. Handling was performed with extra care to avoid any disturbance, which could alter the soil fabric and potentially affect the properties being measured.

3.4 Fabric Characterisation Approach

Soil microstructure direct measurements are labor-intensive and difficult to perform. This study characterized soil microstructure using void ratio, dry density, and estimated pore structure attributes.

A Fabric Index (FI) creates a dimensionless metric on the relative degree of pore and particle structure organization due to the compactive efforts. The FI is determined owing to the behavioural trends of normalized dry density and void ratio, which provides the basis for relative positioning of soil state fabric for various compactive efforts. Therefore, a high FI value indicates a more dense and/or more oriented arrangement of the soil fabric.

In the field of soil mechanics, fabric state characterisation indirectly, most of the time, becomes the only immediate choice due to the lack of direct imaging methodologies. It still provides texture-related evidence.

3.5 Permeability Testing

All of the permeability tests conform to laboratory standard operations. The falling head method was used to measure the vertical hydraulic conductivity of the soils to assess how compaction changed soil fabric and how this change affects the moisture flow behaviours.

Prior to testing, specimens were fully saturated to avoid any entrapment of air. The hydraulic gradient was controlled to guarantee a laminar flow. For each specimen, multiple readings were taken, and the averaged value of hydraulic conductivity was reported for the sake of reliability.

3.6 Testing of Shear Strength

Attributes of shear strength were assessed through the use of direct shear tests, which were performed in a drained state. Specimens were subjected to varying normal pressures to construct the shear strength envelope. The shear stress–displacement response was measured and recorded until peak shear was attained.

Using the results of the tests, the parameters of shear strength which included cohesion (c) and angle of internal friction (φ) were calculated using the Mohr–Coulomb failure criterion. The direct shear test was chosen because of its ease, repeatability, and the advantage of assessing the impact of compaction-related fabric changes on shear resistance.

3.7 Experimental Matrix and Repeatability

All nine compaction conditions were assessed through the integration of three levels of compaction energies and three moisture contents. For each of these conditions, permeability and shear strength tests were performed on specimens that were prepared separately to establish repeatability.

The design of the experiment matrix promoted a more detailed analysis of the relationships between these variables: compaction energy, fabric state, permeability, and shear strength. The reliability of the experimental actions was supported by the consistent trends noted in the repeated testing.

4. Results

4.1 Compaction Characteristics

Figure 5 shows the compaction behaviour of soils under varying energy levels. It illustrates a relationship between the different levels of dry density and moisture content. In the case of the energy levels of compaction, dry density increased with moisture content until the optimum moisture content (OMC) was reached. Thereafter, a decrease in the levels of moisture content resulted in a decrease in the levels of dry density. All other energy levels displayed the same behaviour regarding moisture content levels.

The greatest compaction energy had the greatest impact on achieving the maximum dry density. There was also a minimal decrease in the OMC levels. Under high compaction energy, the maximum dry density was OMC, and the lowest was 1.62 g/cm³ under low compaction energy on the dry side of OMC. This was attributed to an increase in compaction energy, where the classical compaction theory applied again with more rearrangement of the enhanced particles and collapse of the pores due to the added energy. The void ratio levels in table 2 support levels of density which are attributed to an increase in maximum compaction energy.

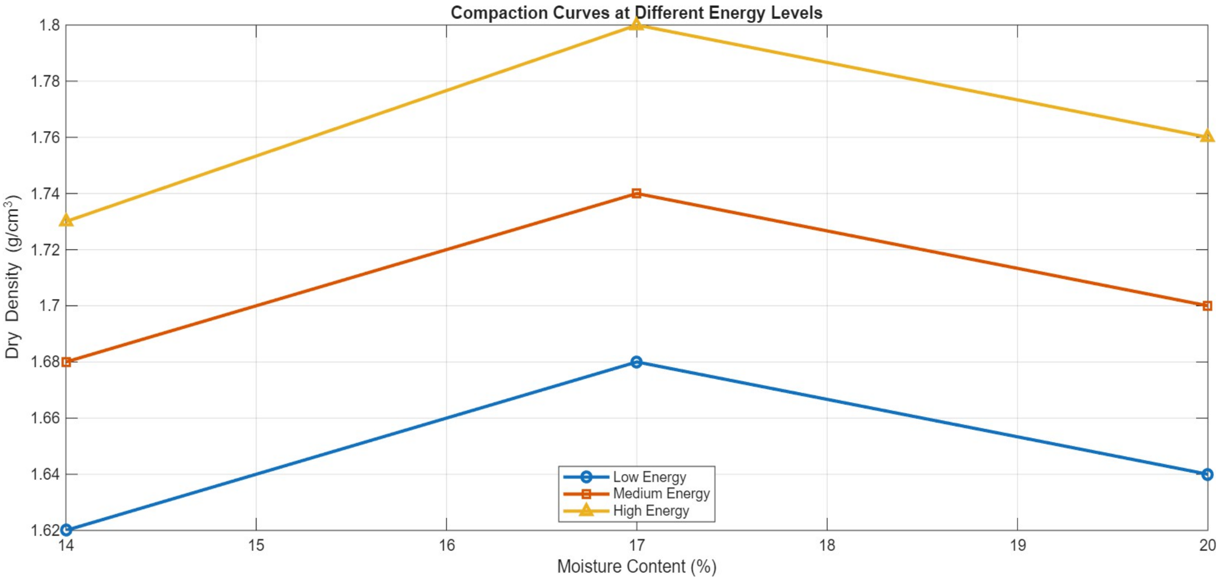

Figure 5: Compaction Curves at Different Energy Levels

Table 2 Dry Density and Void Ratio under Different Compaction Conditions

Compaction Energy	Moisture Content (%)	Dry Density (g/cm³)	Void Ratio
Low	14	1.62	0.66
Low	17 (OMC)	1.68	0.6
Low	20	1.64	0.64
Medium	14	1.68	0.6
Medium	17 (OMC)	1.74	0.54
Medium	20	1.7	0.58
High	14	1.73	0.56
High	17 (OMC)	1.8	0.49
High	20	1.76	0.52

4.2 Variation of Void Ratio and Soil Fabric

Figure 6 illustrates how void ratios change with moisture content and different levels of compaction energy. For every moisture content level, specimens compacted with a higher energy level had a lower void ratio than specimens compacted with a lower energy level. The highest level of compaction energy resulted in a minimum void ratio of 0.49 attained at OMC.

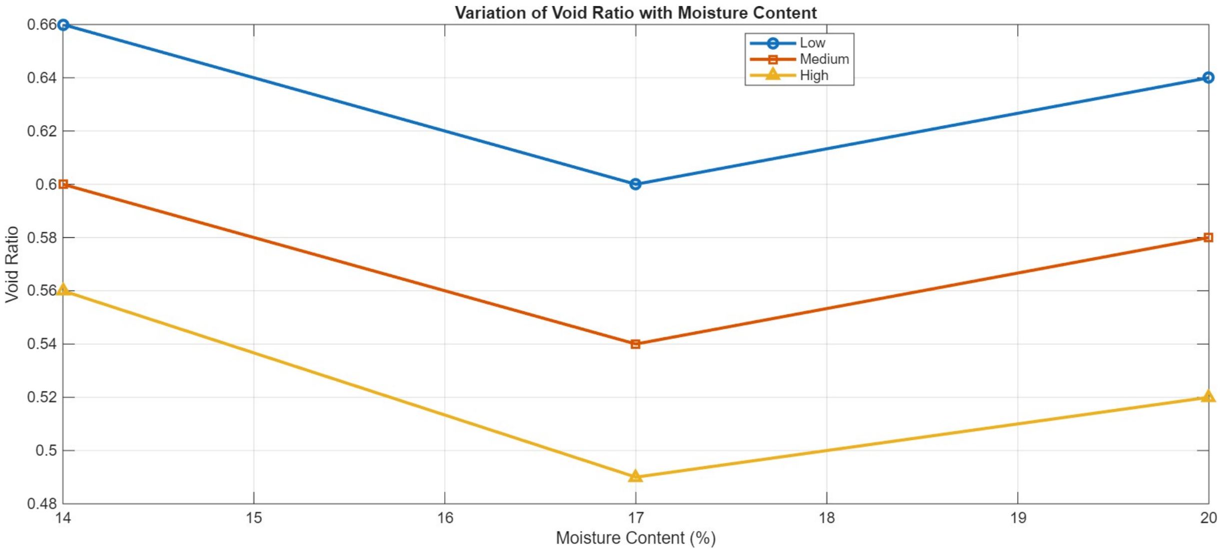

Figure 6: Variation of Void Ratio with Moisture Content

The impact of compaction on the soil fabric was quantified using a dimensionless fabric index (FI). Figure

7 shows the fabric index data, and Table 3 contains the numerical values. The fabric index increased as the energy used during compaction increased, and at every energy level the FI was highest at OMC.

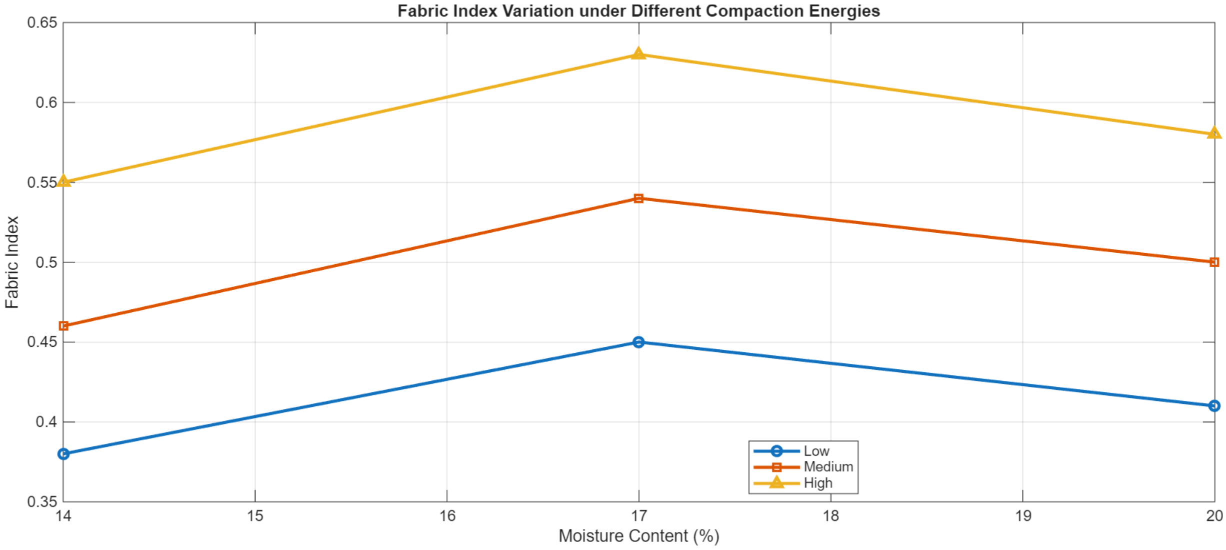

Figure 7: Fabric Index Variation under Different Compaction Energies

The trends noted in the data suggest that increased compaction energy resulted in a more densely packed and better oriented arrangement of soil particles, yielding a more stable and lower aperture pore network. The FI values on the wet side of OMC were slightly lower and suggest that an increase in pore water content caused a minor loosening of the fabric.

Table 3: Fabric Index for Different Compaction States

Compaction Energy	**Moisture Content (%)**	**Fabric Index (FI)**
Low	14	0.38
Low	17	0.45
Low	20	0.41
Medium	14	0.46
Medium	17	0.54
Medium	20	0.5
High	14	0.55
High	17	0.63
High	20	0.58

4.3 Effect of Compaction-Induced Fabric Changes on Permeability

The effects of compaction and soil fabric on hydraulic conductivity are presented in Figure 8, which depicts on a logarithmic scale the changes in soil permeability as a function of moisture content and varying compaction energies. Hydraulic conductivity decreased across all moisture contents as compaction energy increased.

The permeability value of 9.5×10^{-8} m/s under high compaction energy at OMC was the lowest, whereas an OMC value of 4.8×10^{-7} m/s under low compaction energy was the highest. Table 4 presents all data for permeability.

Increasing fabric index and correlating reduction in permeability indicate that densification and particle reorientation in the soil lattice system substantially closed pore spaces and pathways for flow. The permeability increase on the wet side of the OMC is the result of fewer pore spaces after compaction and the creation of larger, less frictional, interparticle water-filled pores.

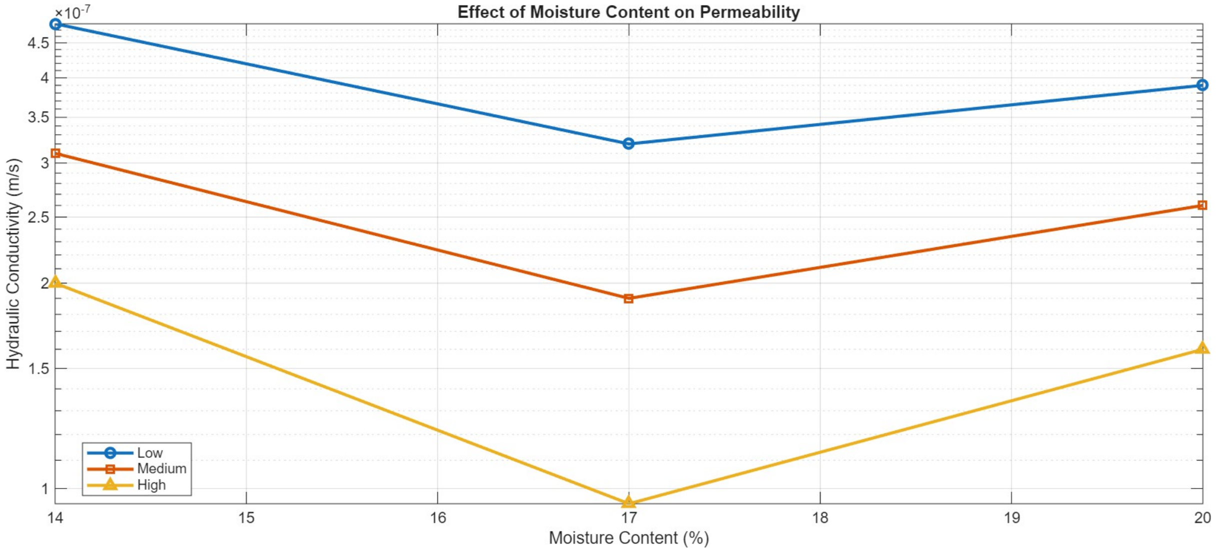

Figure 8: Effect of Moisture Content on Permeability

Table 4: Hydraulic Conductivity under Different Compaction Conditions

Compaction Energy	Moisture Content (%)	Hydraulic Conductivity, k (m/s)
Low	14	4.8×10^{-7}
Low	17	3.2×10^{-7}
Low	20	3.9×10^{-7}
Medium	14	3.1×10^{-7}
Medium	17	1.9×10^{-7}
Medium	20	2.6×10^{-7}
High	14	2.0×10^{-7}

High	17	9.5×10^{-8}
High	20	1.6×10^{-7}

4.4 Shear Strength Response

4.1.1 Cohesion

Figure 9 shows the variation of cohesion with moisture content for different compaction energies and the numerical values are summarised in Table 5. For all moisture contents, cohesion increased with compaction energy. At OMC, cohesion values increased from 22 kPa under low energy compaction to 38 kPa under high energy compaction.

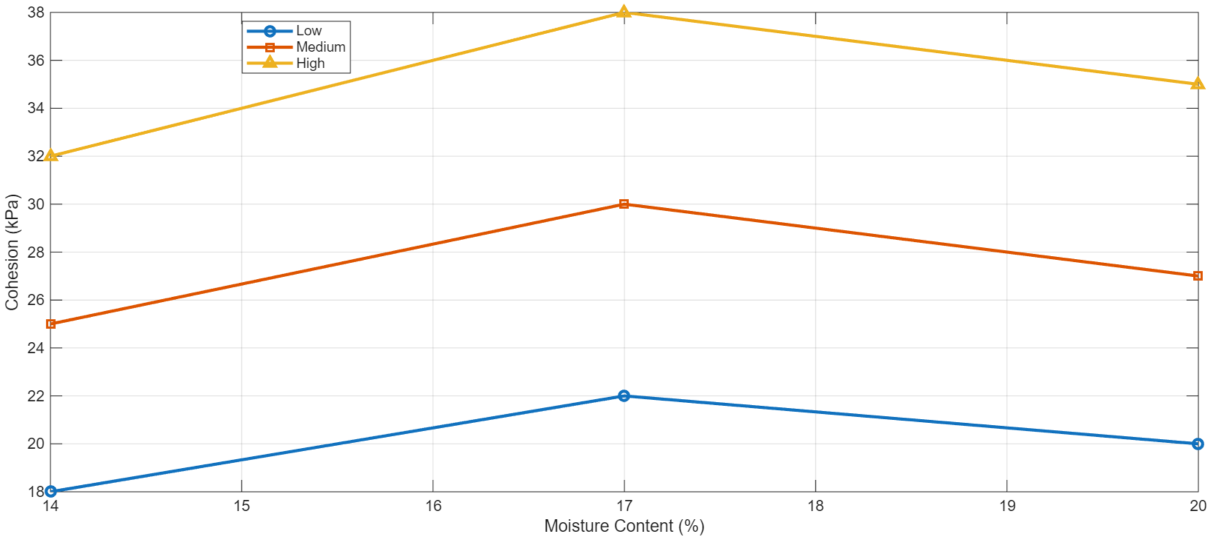

Figure 9: Variation of Cohesion with Moisture Content

The increased cohesion is explained by higher particle interlocking and contact area from fabric densification. A minor reduction in cohesion on the wet side of OMC was recorded which is attributed to the lubricating effect of excess pore water.

Table 5: Cohesion Values from Direct Shear Tests

Compaction Energy	Moisture Content (%)	Cohesion, c (kPa)
Low	14	18
Low	17	22
Low	20	20
Medium	14	25
Medium	17	30

Medium	20	27
High	14	32
High	17	38
High	20	35

4.5 Internal Friction Angle

Figure 10 shows the changes in internal angle of friction with moisture content. Unlike cohesion, the angle of friction shows a relatively smaller range of changes for different levels of compaction energy and moisture content. The angle of friction for the different states ranged from 25.2° to 27.8°. This shows that the frictional resistance is less influenced by the changes in fabric due to compaction as opposed to the cohesive strength.

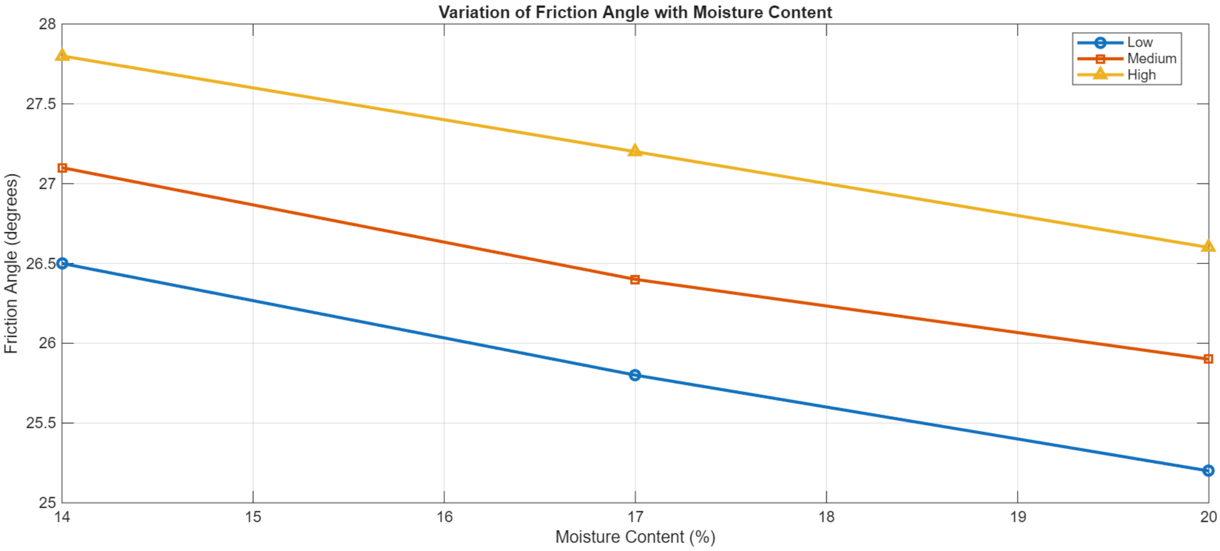

Figure 10: Variation of Friction Angle with Moisture Content

The angle of friction shows that the major cause for the increase in shear resistance due to compaction is the increase in cohesive bonding and fabric densification and not frictional mechanisms.

Table 6: Internal Friction Angle Values

Compaction Energy	**Moisture Content (%)**	**Friction Angle, φ (°)**
Low	14	26.5
Low	17	25.8
Low	20	25.2
Medium	14	27.1

Medium	17	26.4
Medium	20	25.9
High	14	27.8
High	17	27.2
High	20	26.6

4.6 Correlation Between Fabric, Permeability, and Shear Strength

Comprehensively study the role of soil fabric; correlation plots concerning fabric index, permeability, and shear strength were constructed. Fabric index and hydraulic conductivity are inversely correlated in figure 11. Higher fabric index values correspond to lower permeability.

Similar to figure 11, figure 12 shows the relation of fabric index and cohesion and a positive correlation, with FI increasing with cohesive strength. More positive values of FI yield a positive response of cohesive strength.

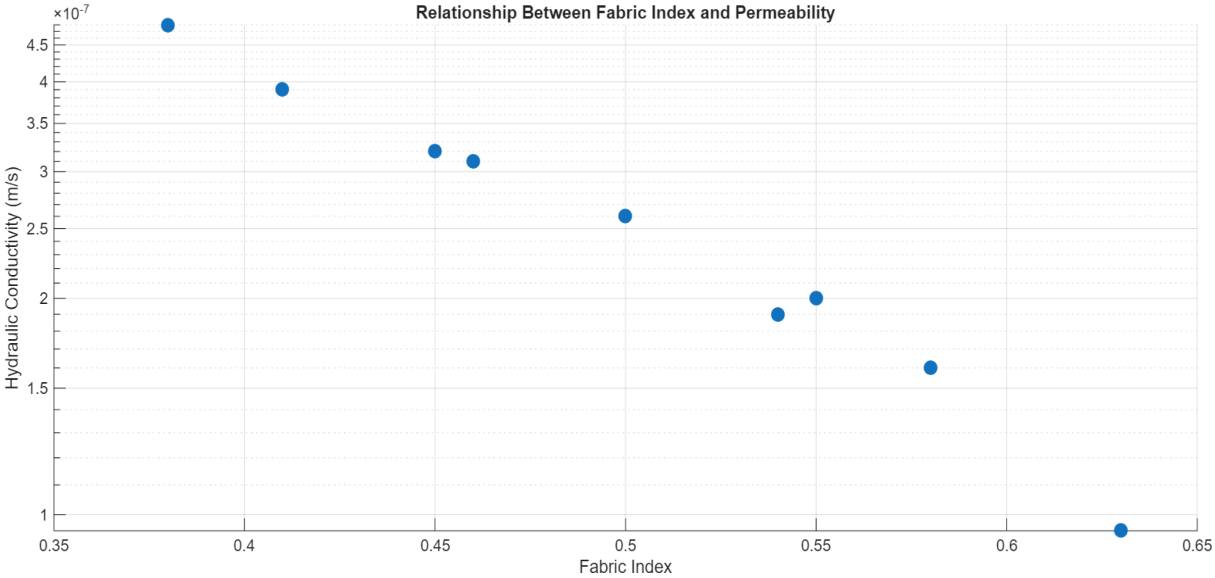

Figure 11: Relationship Between Fabric Index and Permeability

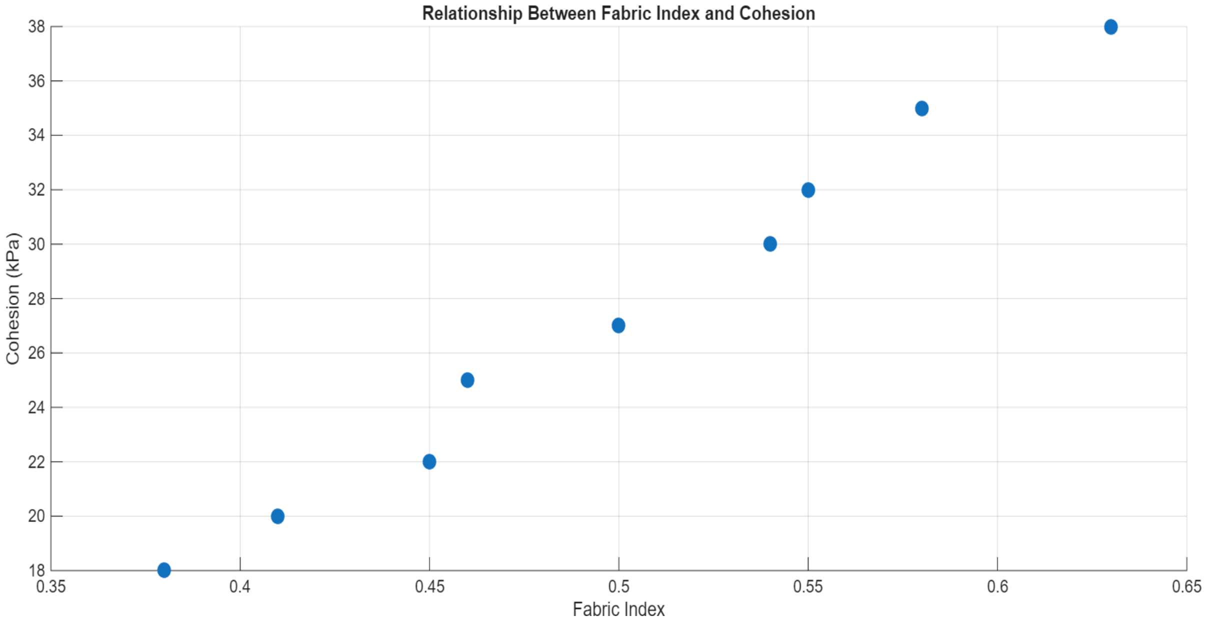

Figure 12: Relationship Between Fabric Index and Cohesion

The inverse relationship of permeability and cohesion in figure 4.9 shows that with the densification of fabric, shear strength is increased and hydraulic conductivity is decreased. The significant relationships obtained show that with the change of fabric due to compaction, the hydraulic and mechanical behaviour of compacted soils is controlled.

5. Discussion

5.1 Influence of Compaction Energy on Soil Fabric Evolution

Soil texture is influenced by a variety of factors, but it appears, based on the data collected, that energy of compaction is the most significant factor. As shown in Table above , the increases and decreases of dry density and void ratios, respectively, demonstrated the advancing changes (i.e. densification) in the soil skeleton with energy of compaction. This densification is also due to the collapse of pores, an increase in interparticle contacts and the rearrangement of particles.

The increase of the fabric index, which in your study is a measure of the variable microstructural changes, is evidence of the increases in the energy of compaction shown in figure also . This results from the increase in compaction effort which yields an increase in the density and the degree of the soil fabric. The highest fabric index for all levels of energy of compaction illustrates the importance of moisture in the rearrangement of the particles.

The stable fabric indices are mostly due to the pore water that is found in the centre of the fabric and it is due to the lack of effective interparticle contacts and the weak fabric in the centre of the fabric. This correlates with the soil compaction mechanisms and the methods of fabric characterisation that were used.

5.2. Behaviour Of Permeability with Respect to Soil Fabric

The results of the hydraulic conductivity tests show a clear relationship with the changes in fabric as a result of the soil compaction process. The relationship between conductivity and compaction energy shows that as the compaction energy is increased for a given moisture content, conductivity tends to decrease. The highest fabric index and lowest permeability values were obtained for a given compaction energy at optimum moisture content.

Soils compacted to higher densities and with higher fabric index values contain less porous and less interconnected voids. During densification, the soil particles position themselves more closely, and the pore spaces between soil particles become more aligned and compacted. The more aligned and compacted porous space and particles lead to an increase in the complexity of flow paths, and thus a decrease in the permeability of the soil matrix. The permeability of soil matrix is thus controlled by the soil fabric, and not by the soil density, as illustrated by the relationship between the soil fabric index and permeability .

The increased permeability on the wet side of the optimum moisture content is associated with the presence of larger, less resistive to flow voids and less resistive to flow regions in the pore matrix. The results show the consideration of optimum moisture content is important in the designing processes for earth structures such as earth dams, embankments, and soil liners when the permeability of the soil is fundamental to the design.

5.3 Effects of Fabric Modification on Shear Strength Parameters

The shear strength results indicate that the effect of changes to the induced fabric of the sample due to compaction is significant for cohesion and relatively insignificant for the internal friction angle. Referring to Fig. 9 and Table 5, cohesion increases, especially at the optimum moisture content, as the compaction energy increases. This trend exemplifies the interparticle bonding that is enhanced, contact area that is increased, and interlocking of the particles that is strengthened within the densified fabric.

On the other hand, the friction angle shows a very small response to varying compaction energies and moisture contents as illustrated in Fig. 10 and Table 6 . This indicates that the resistance to friction is due to the mineralogy of the particles and the roughness of the particles, which do not change with compaction. This is consistent with classical soil mechanics where cohesion is more dependent on the fabric and structure than the friction angle.

The relationship of the fabric index and cohesion indicates that the densification of fabric fills gaps within the material, which in effect increases the cohesion resistance to shear. It means that the increased shear strength of the material due to compaction can be attributed to the compaction providing structural readjustments rather than frictional changes.

5.4 Coupled Hydraulic–Mechanical Response

Fabric modification has revealed the coupled relationship between shear strength and permeability for the first time in this study. The permeability-cohesion relationship demonstrated in Figure 11 showcases the fact that, while compaction and the associated densification of the soil fabric occur, hydraulic conductivity decreases and shear strength increases.

There are varying consequences of this coupled response, specifically focused on geotechnical applications. More specifically, in earth dam cores and liners, overly compacted soil can become brittle under load. Thus, there is an understanding that compacted soils in these barriers increase the overall benefit of barrier performance due to lower permeability. Knowing the self-interaction hydraulic-mechanical properties of fabric the soils allow for an overall optimized compaction strategy, defining the permeability and strength thresholds.

The fabric index already suggested in this study is less complicated than attempting to link advanced microstructural testing to performance.

5.5 Engineering Implications

The findings of this research are pertinent to the field of compaction, more specifically the evidence obtained suggests that the combination of compaction in the vicinity of the optimum moisture content coupled with requisite energy expended would result in the achievement of a dense and stable soil fabric which evidenced low permeability and high shear strength.

Moisture level during compaction for subgrades, embankments, and compacted liners must be as rigorously managed as compaction energy. The sensitivity of permeability and cohesion to changes in fabric suggests that quality control measures are required that go beyond compliance with a density specification.

6. CONCLUSIONS

A systematic experimental programme was conducted to examine the compaction-induced evolution of soil fabric in a low-plasticity clay and its coupled effects on saturated hydraulic conductivity and direct shear strength parameters. Nine compaction states — spanning three energy levels and three moisture conditions — were investigated using a dimensionless Fabric Index as the primary fabric descriptor. The following conclusions are drawn from the experimental results and their analysis:

1) **Compaction energy is the dominant driver of soil fabric densification.** Increasing compaction energy from low to high progressively reduced the void ratio from 0.66 to 0.49 and increased dry density from 1.62 to 1.80 g/cm³ at OMC, with corresponding gains in the Fabric Index from 0.45 to 0.63. Optimum moisture content consistently produced the highest degree of fabric organisation at every energy level, confirming that the combined effect of energy and moisture — not energy alone — governs the microstructural state of the compacted soil mass.
2) **Soil fabric is the primary determinant of hydraulic conductivity in compacted clays.** A strong inverse relationship was established between the Fabric Index and hydraulic conductivity across all compaction states. The minimum hydraulic conductivity of 9.5×10^{-8} m/s was achieved under high compaction energy at OMC — approximately five times lower than the maximum of 4.8×10^{-7} m/s recorded at low energy on the dry side. Soils compacted dry of optimum exhibited higher permeability due to larger, more interconnected macropores, whereas wet-side compaction produced a modest permeability increase relative to OMC, attributable to the development of larger, water-filled inter-aggregate pores. These findings confirm that fabric-mediated flow tortuosity, rather than bulk density per se, governs hydraulic conductivity in compacted fine-grained soils.
3) **Cohesion is the shear strength parameter most sensitive to compaction-induced fabric change; internal friction angle is not.** Cohesion increased from 18 kPa (low energy, dry of OMC) to 38 kPa (high energy, OMC), exhibiting a strong positive correlation with the Fabric Index. This increase reflects enhanced interparticle contact area, interlocking, and bonding within the densified fabric. In contrast, the internal friction angle varied only narrowly

between 25.2° and 27.8°, confirming that frictional resistance is governed primarily by particle mineralogy and morphology — characteristics that are independent of compactive effort — rather than by fabric state. Fabric-induced shear strength enhancement therefore operates principally through cohesive mechanisms.

4) **A coupled inverse relationship exists between permeability and cohesion, with soil fabric as the governing variable.** The simultaneous increase in cohesion and decrease in hydraulic conductivity with increasing fabric organisation establishes that soil fabric acts as a unified mediating variable for both hydraulic and mechanical behaviour. This coupled response has direct implications for the design of earth structures in which low permeability and high shear strength are simultaneously required — the Fabric Index provides a single, tractable metric for assessing the degree to which both objectives are met under a given compaction state.
5) **Performance-based compaction specifications that incorporate fabric state are required for critical geotechnical applications.** Current practice, which specifies compaction targets in terms of relative density or percent compaction, provides no direct information about the microstructural state of the compacted soil. The Fabric Index proposed in this study — derived entirely from standard macroscopic measurements (dry density and void ratio) — provides a practical, accessible fabric descriptor that can be computed without advanced imaging technology. Adoption of fabric-aware compaction criteria in earth dam construction, liner design, and pavement subgrade engineering would enable simultaneous optimisation of hydraulic and mechanical performance, reducing uncertainty in the long-term behavior of compacted earth structures.

Collectively, these findings demonstrate that the engineering performance of compacted soils is mediated by fabric — not merely by density — and that the coupled hydraulic–mechanical response to compaction can be characterised through a single dimensionless index. The Fabric Index framework developed herein bridges the conceptual gap between advanced microstructural investigations (requiring SEM or CT imaging) and routine geotechnical laboratory practice, offering a scalable methodology for fabric-informed compaction quality control.

7.Limitations and Future Work

Although this study offers a systematic experimental account of compaction-induced fabric changes and their coupled effects on hydraulic conductivity and shear strength, several limitations should be recognised when interpreting the findings. Soil fabric was characterised indirectly using macroscopic state variables - dry density, void ratio, and the derived Fabric Index — rather than through direct microscale observation. Techniques such as scanning electron microscopy (SEM) and X-ray computed tomography (CT), which can resolve pore geometry, particle orientation, and aggregate structure at the microscale, were not employed. Their adoption in future studies would provide independent validation of the fabric trends inferred from the Fabric Index and strengthen the mechanistic basis of the proposed framework.

A further limitation concerns the scope of permeability characterisation. Hydraulic conductivity was measured exclusively in the vertical direction under fully saturated conditions, whereas compaction-induced particle reorientation is known to produce directional differences in hydraulic behaviour. Anisotropic permeability assessment, together with unsaturated hydraulic conductivity functions derived from soil-water characteristic curve (SWCC) testing, should be incorporated in subsequent investigations to better represent the partially saturated conditions that prevail in field-compacted earth structures. In addition, the experimental programme was confined to a single low-plasticity clay, and the applicability of the Fabric Index framework to soils of higher plasticity, different mineralogy, or expansive character warrants systematic verification across a broader range of materials. Finally, shear strength was evaluated solely under monotonic drained loading; the influence of cyclic loading, stress-path dependence, and long-term environmental phenomena such as repeated wetting–drying cycles on compaction-induced fabric and its associated mechanical response was not addressed, yet these factors are essential for a comprehensive assessment of durability in real service conditions.

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Future Research Scope

Future research should address these limitations by extending the Fabric Index framework in several directions. Integration of the proposed index into constitutive modelling frameworks- particularly fabric-sensitive formulations within Critical State Soil Mechanics or elasto-plastic unsaturated soil mechanics -would enable fabric-explicit prediction of compacted soil behaviour under complex stress paths and environmental loading conditions. Equally important is the development of field-applicable methodologies for real-time Fabric Index estimation during compaction operations, potentially through non-destructive testing approaches such as electrical resistivity or ground-penetrating radar. Such tools would facilitate the practical transition from conventional density-based compaction control to a performance-based approach that directly accounts for the microstructural state of the compacted soil, ultimately improving the reliability and long-term serviceability of compacted earth structures.

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