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Long-term Effects of Munisipal Solid Waste Leachate on Soil Geotechnical Properties

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Abstract

This study investigates the long-term effects of landfill leachate contamination on soil hydraulic conductivity and shear strength parameters over a 12-month period, addressing the current lack of comprehensive long-term experimental data in this field. Laboratory permeability tests and direct shear tests were performed on sandy clayey silt samples contaminated with leachate at concentrations ranging from 5% to 25%. Microstructural and mineralogical analyses were conducted using SEM and XRD to identify the mechanisms behind observed changes. The results identify a critical threshold at 15% contamination where soil behavior transitions from granular to cohesive characteristics, marked by significant changes in both hydraulic and mechanical properties. Hydraulic conductivity increases at low contamination levels but decreases significantly at higher levels, while friction angle shows an immediate reduction from 36.5° to 31-31.5° and cohesion exhibits a three-phase evolution pattern, reaching peak increases of 151.5% at 15% contamination. The hydraulic conductivity changes are controlled by contamination level rather than exposure time, maintaining stable values throughout the testing period, whereas shear strength parameters demonstrate more complex temporal evolution patterns. These findings provide essential parameters for landfill design and stability assessment, demonstrating how leachate concentration affects long-term soil behavior through mineral formation and structural modification.

Keywords

hydraulic conductivity, shear strength, landfill leachate, soil contamination, soil permeability, microstructural analysis

1 Introduction

The structural integrity and environmental impact of landfills extend far beyond their physical boundaries, with soil contamination through leachate migration representing one of the most significant long-term environmental concerns. The stability of these facilities critically depends on both the waste body's geotechnical properties and, more fundamentally, the characteristics of the foundation soil. When these properties undergo modification through leachate interaction, the risk of structural failure increases substantially, potentially leading to catastrophic environmental consequences [1]. Understanding how leachate affects both the hydraulic and mechanical properties of foundation soils becomes crucial for ensuring long-term landfill stability and environmental protection [2]. Recent incidents, such as the Koshe Landfill failure in Ethiopia in 2017 [3], which resulted in 115 fatalities, highlighting the critical importance of comprehending how leachate affects soil behavior and stability over time.

Landfill leachate, a complex mixture generated through waste decomposition and water infiltration, contains diverse organic and inorganic compounds, including biodegradable matter, heavy metals, and various chemical constituents [4, 5]. The interaction between these components and surrounding soil can significantly alter hydraulic conductivity and shear strength parameters, directly influencing both contaminant transport patterns and overall landfill stability. Modifications in soil permeability can create unexpected leachate migration pathways, potentially compromising containment systems [6, 7], while changes in shear strength parameters directly affect slope stability and bearing capacity [8–10]. Together, these properties determine the overall integrity of the waste depo system and its long-term stability. The permeability characteristics of soils affected by contamination serve as a fundamental parameter in multiple crucial elements of landfill engineering design and operation. This property not only dictates

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the overall efficacy of waste containment facilities but also substantially influences the configuration and performance of leachate management infrastructure [11, 12]. When considered alongside modifications in shear strength parameters, these permeability alterations significantly impact foundation stability through their influence on pore pressure distribution patterns and the resulting effective stress conditions within the soil mass. Furthermore, hydraulic conductivity plays a crucial role in environmental impact evaluation, as it controls the rate and extent of potential contaminant transport into adjacent soil zones and aquifer systems [1, 13]. The interconnected nature of these geotechnical properties takes on particular significance, as alterations in one characteristic frequently trigger corresponding changes in others through complex modifications of the soil's microstructure and mineral composition.

Current research has predominantly focused on short-term leachate-soil interactions, creating a significant knowledge gap regarding long-term effects. While studies have demonstrated that leachate can modify soil properties [14], these investigations typically cover brief exposure periods, leaving crucial questions about long-term behavior unanswered [6]. This limitation is particularly concerning given that landfills remain active sources of contamination for decades after closure.

This research addresses this critical knowledge gap by examining the evolution of soil engineering parameters under various degrees of leachate contamination over a 12-month period. Through comprehensive analysis of different contamination levels (5–25%) and their temporal effects, this study aims to:

- Develop improved design criteria for new landfill systems
- Enhance risk assessment methodologies for existing facilities
- Establish more effective long-term monitoring protocols
- Inform evidence-based remediation strategies for contaminated sites

The findings provide quantitative data on the relationship between contamination levels and soil property changes over time, directly contributing to the advancement of landfill engineering practices and environmental protection strategies.

2 A Brief Review of Soil Leachate interaction

The interplay between landfill leachate and the surrounding soil matrix presents a multifaceted environmental and geotechnical phenomenon that remains a critical focus area for scientific investigation and engineering practice. This interaction encompasses intricate processes involving chemical, biological, and physical mechanisms that collectively alter the mechanical behavior of soil systems.

2.1 Soil leachate interaction processes

2.1.1 Chemical Processes

The chemical alterations occurring between soil and leachate manifest through three distinct yet interconnected pathways, each making unique contributions to the transformation of soil properties.

The initial mechanism involves sorption phenomena, which integrates both adsorption and absorption processes, with efficacy determined by the specific characteristics of both soil composition and leachate properties. Research by Kjeldsen et al. [15] revealed that organic matter concentration in soils directly correlates with enhanced organic contaminant sorption capabilities, while clay mineral content proves instrumental in metal ion retention. These sorption dynamics significantly influence both contaminant mobility patterns and overall soil mechanical response.

The second mechanism incorporates precipitation and dissolution phenomena, which exert fundamental control over metal ion mobility within the soil framework. Mitchell and Madsen's [16] investigations highlighted the critical role of pH conditions in these reactions, demonstrating that alkaline conditions facilitate metal precipitation and subsequent immobilization, whereas acidic environments promote increased metal mobility. This pH-dependent behavior establishes a dynamic equilibrium where environmental fluctuations can initiate substantial changes in soil-leachate chemical interactions [17, 18].

The third mechanism involves oxidation-reduction reactions, particularly significant for metallic elements including iron, manganese, and sulfur compounds. Joseph and colleagues [18] established that landfill maturity significantly influences these processes, as older facilities typically establish reducing conditions that enhance metal immobilization through sulfide compound formation. This time-dependent aspect of soil-leachate interactions introduces additional complexity to the prediction of long-term geotechnical performance.

2.1.2 Physical Processes

The physical transformations primarily manifest through alterations in the soil's structural configuration and pore network characteristics. Contemporary research has demonstrated that leachate infiltration induces substantial modifications to soil physical attributes, with effects varying significantly across different depths from waste disposal locations [19]. A predominant physical mechanism involves the progressive obstruction of soil void spaces, which occurs through multiple parallel processes:

- Mechanical clogging through the accumulation of suspended particulate matter
- Chemically-induced pore blockage resulting from mineral precipitation processes
- Biological pore occlusion arising from microbial proliferation and biofilm development

These interconnected mechanisms have been demonstrated to fundamentally alter the soil's hydraulic behavior, particularly affecting its capacity for fluid transmission and moisture retention capabilities [20]. The resulting modifications to the soil's pore network architecture play a crucial role in determining its overall engineering performance.

2.2 Effect of leachate on soil geotechnical properties

The introduction of landfill leachate into soil systems triggers substantial modifications across multiple geotechnical parameters, encompassing alterations in strength characteristics, hydraulic conductivity, compaction characteristics, and consistency limits.

2.2.1 Modifications to Strength Parameters

Research examining leachate's influence on soil strength characteristics reveals diverse responses across varying soil classifications. Within lateritic soil formations, certain investigations documented enhanced cohesion accompanied by reduced friction angles, attributed to clay content augmentation [21, 22], while alternative studies observed degradation in both parameters due to particle dispersion [23]. Investigations of clay soils consistently demonstrate substantial strength modifications, though the precise nature of these alterations exhibits considerable variability [24]. Recent research indicates that the magnitude of leachate-induced effects correlates strongly with contamination concentration and stress state conditions, with highly contaminated specimens exhibiting pronounced ductile response characteristics [25, 26]. Understanding microscopic changes in mineral compositions and soil structure [27] may be key to explaining these varied effects.

2.2.2 Alterations in Hydraulic Conductivity

The evolution of soil permeability under leachate exposure follows intricate temporal patterns that critically influence waste containment system effectiveness. Initial exposure typically results in permeability reduction through three principal mechanisms: mechanical obstruction by suspended matter, chemical precipitation within void spaces, and biological clogging through microbial colonization and biofilm development [28, 29]. Recent investigations demonstrate particularly pronounced initial modifications in fine-grained materials, where suspended leachate particles effectively clog smaller pore networks [20].

Extended exposure periods often result in permeability enhancement as acidic leachate constituents dissolve soil particles and degrade cementing compounds [30], establishing new flow channels and fundamentally altering soil structure. Research conducted by Ale [19] demonstrates significant variation in these modifications with depth from disposal zones, emphasizing the importance of spatial variability consideration. The extent of these alterations varies significantly with soil type, as demonstrated through comprehensive field studies at various dumpsites [20].

Leachate characteristics itself, including pH values, ionic composition, and biological activity levels, fundamentally influence these transformations. Recent investigations indicates that modern waste compositions induce different modification patterns compared to historical observations [29]. These parameters influance both the rate and nature of permeability alterations, significantly impacting long-term containment system performance. Research indicates that dramatic permeability increases observed in certain cases may be specific to particular soil-leachate combinations and should not be generalized across all situations [31]. From a practical engineering perspective, these findings emphasize the critical importance of appropriate material selection and systematic monitoring protocols for containment systems.

2.2.3 Effect on soil compaction

The literature findings demonstrate considerable variability in leachate's influence on soil compaction behavior, particularly regarding its effects on Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), with observed responses varying based on both soil classification and leachate chemical composition [29]. Field-based studies indicate that these modifications exhibit significant spatial variation, both with depth and distance from contamination sources [20].

The underlying mechanisms responsible for these alterations encompass both physicochemical processes. Studies have shown that leachate contamination can lead to mineral dissolution and increased void ratios in some cases, while in others, particle aggregation in highly concentrated leachate results in increased density [14, 30, 32, 33]. A critical mechanism identified in these interactions involves the lubricating influence of leachate on soil particles, which significantly impacts OMC values and subsequently affects material workability and compaction response characteristics [26]. From a practical perspective, these findings have important implications for construction in and around contaminated sites [34, 35].

3 Materials and methods

The current study employed a comprehensive experimental approach to quantitatively evaluate the effects of Municipal Solid Waste (MSW) leachate contamination on the geotechnical parameters of soil, with a particular focus on soil permeability. The experimental design was structured to assess both the immediate and long-term impacts of leachate contamination on soil permeability.

The investigation focused on the following key aspects:

1. Contamination Levels: Soil samples were prepared with varying degrees of leachate contamination from 5 to 25% to simulate different exposure scenarios.
2. Temporal Analysis: To capture the evolution of soil properties over time, tests were conducted at specific intervals: immediately after contamination, and at 1, 3, 6, 9, and 12 months post-contamination.

To further understand the mechanical changes of soil, Scanning Electron Microscopy (SEM) was employed on the samples. XRD tests were used to identify the chemical changes.

3.1 Leachate characteristics

The leachate used in this study was obtained directly from the leachate collecting system of the Pusztazámor landfill in Hungary. This approach was chosen to preserve the initial characteristics of the leachate, ensuring that the experimental conditions closely mirrored real-world scenarios. The chemical properties of the leachate were thoroughly analyzed to provide a comprehensive understanding of its composition and potential effects on soil parameters (Table 1).

Table 1 Leachate chimical characteristics

Leachate characteristics	
pH	7.95
Specific electrical conductivity (25 °C) (μS/cm)	10230
Hydrogencarbonate (mg/l)	2867
Carbonate (mg/l)	<3
Total alkalinity (mmol/l)	47.0
Total hardness (CaO mg/l)	185
Chemical Oxygen Demand (COD)	544
Sulfate (mg/l)	58
Nitrate (mg/l)	19.0
Chloride (mg/l)	2140
Phosphate (mg/l)	0.16
Ammonium (mg/l)	442
Iron (mg/l)	2.77
Manganese (mg/l)	104
Sodium (mg/l)	1960
Potassium (mg/l)	1280
Magnesium (mg/l)	47.4
Calcium (mg/l)	54.3

3.2 Soil characteristics

The tested soil is collected from the same landfill and used as leveling soil under the lining system as it is the naturally available soil in the landfill location. It is a well-graded sandy clayey silt, characterized by 32.64 % silt with significant sand content (57.5%), minor clay fraction (8.29%), and minimal gravel (1.57%). The soil exhibits low plasticity (IP = 4.9%) with liquid and plastic limits of 25.5% and 20.7%, respectively. Physical properties include a natural water content of 13.3%, solid density of 2.66, void ratio of 0.85, and degree of saturation of 0.31. The soil's grain size distribution shows uniformity (C_u = 17.18) and curvature (C_c = 2.06) coefficients indicative of well-graded material. The hydraulic conductivity ($k = 6.428 \times 10^{-7}$ m/s) indicates low permeability, while direct shear tests reveale 10.3 kPa and φ' = 36.5°, and similar residual values (C_r' = 8.8 kPa, φ_r' = 36.5°). All tests were conducted following relevant ISO standards.

3.3 Sample preparation

The preparation of soil samples for this study was conducted with thorough attention to detail to ensure consistency and reliability of results. The process was designed to simulate various degrees of leachate contamination and to allow for the observation of long-term effects on soil properties.

Soil samples were carefully mixed with MSW leachate to create a range of contamination levels. The concentrations of leachate used were 5%, 10%, 15%, 20%, and 25% relative to the soil's dry weight. This spectrum of contamination levels was carefully selected to encompass a wide array of potential real-world scenarios, from mild contamination to severe leachate exposure.

Following the preparation, each contaminated soil sample was transferred to an airtight dark container.

These containers were designed to isolate the samples from external environmental factors that could influence the chemical reactions within leachate soil interaction. All prepared samples were stored in a controlled laboratory environment maintained at a constant temperature of 25 °C.

As the key aspect of this study was the investigation of the long-term effects of leachate contamination on soil properties, the prepared samples were conditioned over an extended period of 12 months. This permits the complete interaction between the soil particles and leachate components allowing the potential chemical reactions to reach equilibrium and assessment of any time-dependent changes in soil microstructure or geotechnical properties

3.4 Testing procedures

To assess the impact of MSW leachate contamination on the geotechnical properties of the soil, a comprehensive suite of laboratory tests was conducted on each sample. These tests were performed in accordance with the relevant ISO standards and included:

- Hydraulic Conductivity Test (ISO 17892-11:2019) [36]: The falling head method was employed to determine the hydraulic conductivity of the soil samples.
- Direct Shear Test (ISO 17892-10:2018) [37]: Shear strength parameters were determined using a direct shear apparatus of 60 × 60 mm shearing area. The shearing speed was set to a constant rate of 0.5 mm/minute with a total displacement of 20 mm. To evaluate the behavior of the soil under various loading conditions, a wide range of normal loads of 50 kPa, 100 kPa, 200 kPa, 300 kPa, 400 kPa, and 500 kPa was adopted.

To fulfill the objective of long-term evaluation of the geotechnical change, for each contamination level (5%, 10%, 15%, 20%, and 25% leachate content), these tests were conducted after 1 month, 3 months, 6 months, 9 months, and 12 months (see Fig. 1).

To further characterize the soil and assess potential microstructural changes due to contamination, Scanning Electron Microscopy (SEM) was employed. Samples were air-dried prior to scanning. To improve the conductivity of electrons for a better resolution, the samples were gold-plated. SEM images were taken of both uncontaminated soil samples and samples exposed to MSW leachate.

X-ray diffraction (XRD) analyses were conducted on both uncontaminated and contaminated soil samples to identify mineralogical changes induced by leachate-soil chemical interactions, providing insights into the mechanisms behind observed mechanical property alterations.

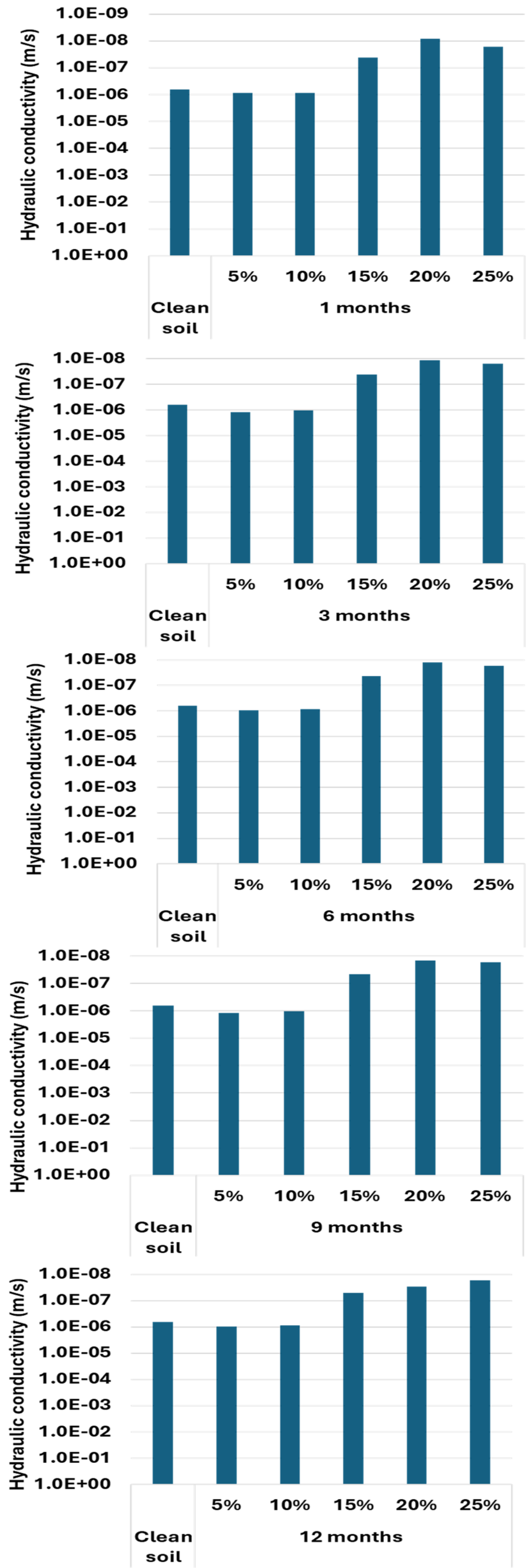

Fig. 1 Evolution of hydraulic conductivity of leachate-contaminated soil

4 Results

The introduction of leachate into the soil matrix resulted in complex alterations to the soil's characteristics, with effects varying considerably depending on the level of contamination and exposure time, showing a constant pattern during the 12 months of curing time.

4.1 Permeability test results

4.1.1 Contamination Level Effects

At low contamination levels (5-10%), these levels led to a slight increase in hydraulic conductivity. This initial increase is attributed to the leachate's effect on soil structure, possibly causing dispersion of fine particles and creating preferential flow paths. This suggests that at low concentrations, the leachate may act as a dispersing agent, temporarily enhancing the soil's ability to transmit water. Despite these fluctuations, permeability for both levels (5-10%) remains elevated above the clean soil value even after 12 months, suggesting a lasting alteration of soil structure at these contamination levels.

A significant behavioral shift occurred at 15% contamination and beyond. At 15%, hydraulic conductivity decreased dramatically to $4.172E^{-08}$ m/s (93.5% reduction from clean soil). Higher contamination levels (20-25%) showed even more severe reductions, respectively, to $8.545E^{-09}$ m/s (98.7% reduction) and $1.65E^{-08}$ m/s (97.4% reduction). These significant decreases suggest severe soil structure alterations, likely due to combined effects of physical pore clogging, and chemical alterations of clay particles induced by high leachate concentrations.

4.1.2 Time-Dependent Effects

The analysis of hydraulic conductivity evolution revealed that changes are predominantly governed by contamination level rather than exposure duration, with permeability values remaining remarkably stable throughout the 12-month period for each contamination level. This time-independent behavior suggests that the structural modifications affecting hydraulic conductivity occur rapidly upon initial exposure to leachate and establish a new stable configuration that persists over time.

4.2 Shear strength results

The clean soil exhibited initial shear strength parameters with a friction angle (φ) of 36.5° and cohesion (C) of 10.3 kPa in peak conditions, with residual values of 36.5° and 8.8 kPa respectively. Upon introduction of leachate, these parameters underwent substantial modifications, varying with both contamination level and exposure duration.

4.2.1 Contamination Level Effects

The impact of leachate contamination on soil shear strength parameters demonstrated distinct patterns across different contamination levels, revealing complex interactions between the leachate and soil matrix. At low contamination levels (5-10%), the soil exhibited moderate alterations in its shear strength parameters (Fig. 2). The friction angle decreased to values between 31-31.5°,

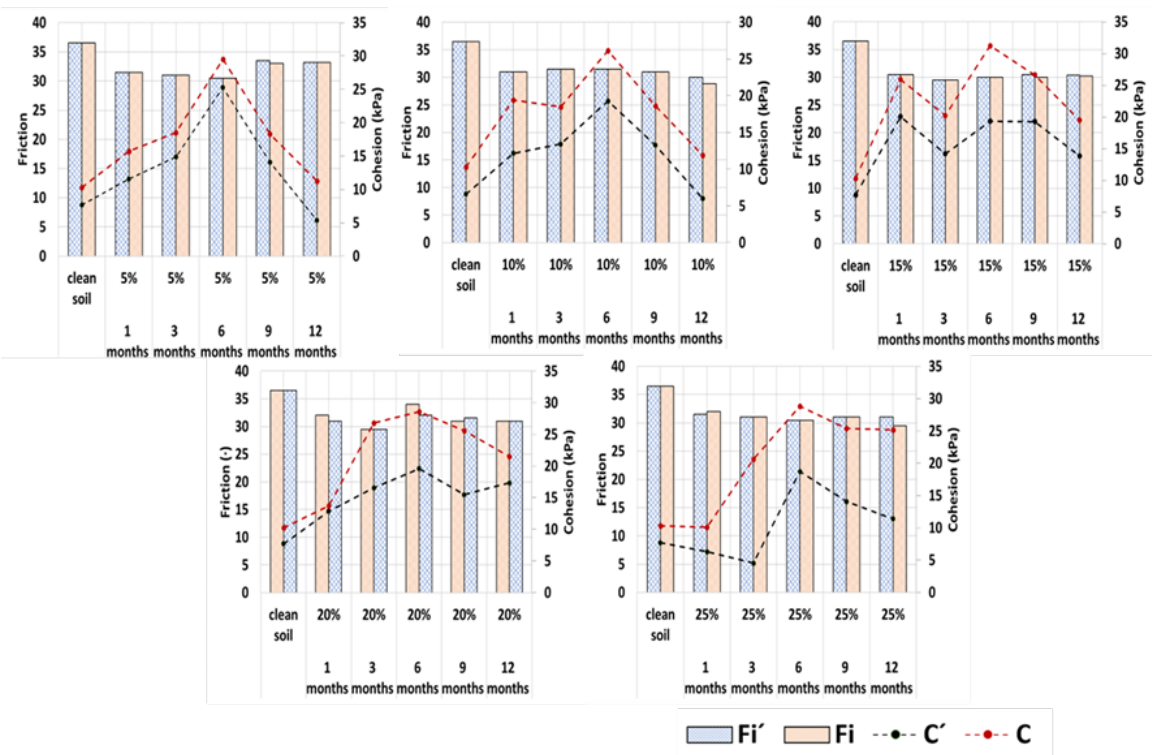

Fig. 2 Evolution of friction angle with the degree of contamination

representing approximately a 13.7-15.1% reduction from the initial value. Simultaneously, the peak cohesion showed a notable increase to 15.7-19.4 kPa, marking a 52.4-88.3% increase from the initial value. The initial increase in cohesion at low contamination levels (5-10%) corresponds with findings by Kumar et al. [38], and Khodary et al. [31], who reported cohesion increases in similar conditions for silty clays.

The 15% contamination level emerged as a notable threshold in the soil's initial response to leachate exposure. At this concentration, the soil experienced a significant reduction in friction angle, decreasing to 30.5° (a 16.4% reduction), while simultaneously showing a substantial increase in peak cohesion, reaching 25.9 kPa (a 151.5% increase from the initial value).

Higher contamination levels (20-25%) produced more complex and variable behavior in the soil. The friction angle initially showed a lesser reduction to 32° (12.3% reduction) compared to the 15% concentration but exhibited continued degradation over time. This pattern of friction angle reduction across contamination levels aligns with several previous studies, Du et al. [39] reported similar reductions in friction angle for contaminated clayey soils, closely matching our findings. The cohesion exhibited particularly complex responses at higher contamination levels. During the initial exposure periods (1-3 months), the soil showed varying responses, with 20% contamination resulting in a moderate increase to 13.7 kPa (33% increase), while 25% contamination showed minimal change (10.1 kPa, 2% decrease).

4.2.2 Time-Dependent Effects

The evolution of shear strength parameters over time revealed distinct phases of soil-leachate interaction, demonstrating the dynamic nature of the contamination process (Fig. 3). In the short term (1-3 months), the soil showed immediate responses to leachate introduction across all contamination levels. The friction angle experienced an immediate reduction, while cohesion showed variable increases depending on the contamination level. Low contamination levels (5-10%) produced moderate increases in cohesion (52-88%), while the 15% concentration resulted in the most dramatic initial increase (151.5%).

The medium-term period (3-6 months) marked a phase of continued evolution in soil strength parameters. Friction angles remained relatively stable but reduced, with values

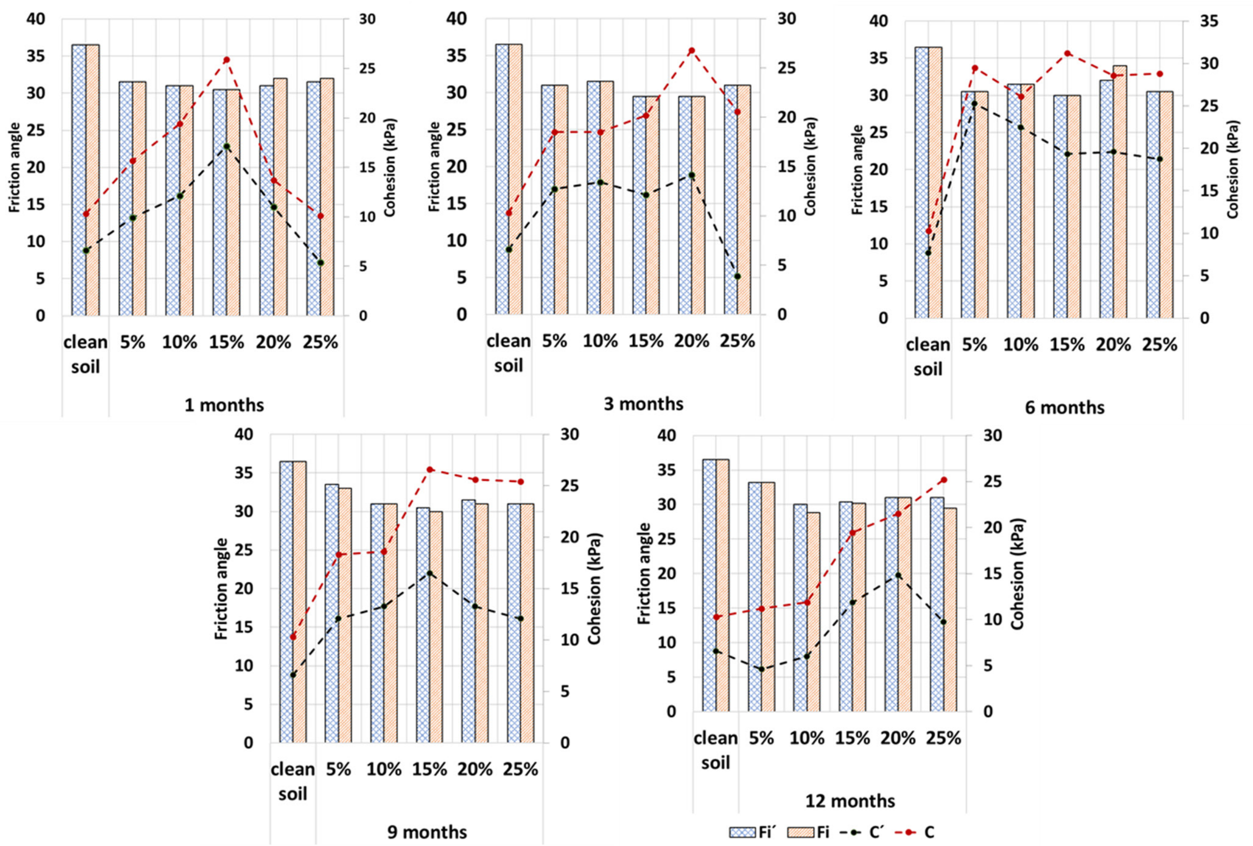

Fig. 3 Evolution of shear data with Time

between 29.5-34°. Cohesion values generally increased during this period, with peak values typically ranging from 25-31 kPa across different contamination levels.

Long-term exposure (9-12 months) revealed a general trend of parameter degradation, contrary to any recovery. Friction angles showed a further reduction, with final values ranging from 28.8° to 33.2°, with most samples stabilizing between 29-31°. Cohesion values showed significant variation by 12 months, ranging from 11.22 kPa to 25.2 kPa, with the highest values observed at 20% contamination (25.2 kPa, 144.7% increase from clean soil). This observation indicates that the long-term effects of leachate.

5 Discussion

The interaction between leachate and soil produces complex modifications in both hydraulic and mechanical properties, with distinct patterns emerging at different contamination levels. These modifications demonstrate the interconnected nature of soil fabric changes and their influence on engineering properties.

At low contamination levels (5-10%), the soil exhibits its behavior characteristic of granular materials. The slight increase in hydraulic conductivity correlates with the soil dispersion and the partial dissolution of carbonate minerals, evidenced by decreased peak intensities of dolomite and calcite in XRD analysis (Fig. 4). This initial phase suggests that leachate acts as a dispersing agent, temporarily enhancing the soil's ability to transmit water through the creation of preferential flow paths. This dissolution process simultaneously affects the soil's shear properties, leading to a reduction in friction angle (13.7-15.1%) while increasing cohesion (52.4-88.3%). The creation of preferential flow

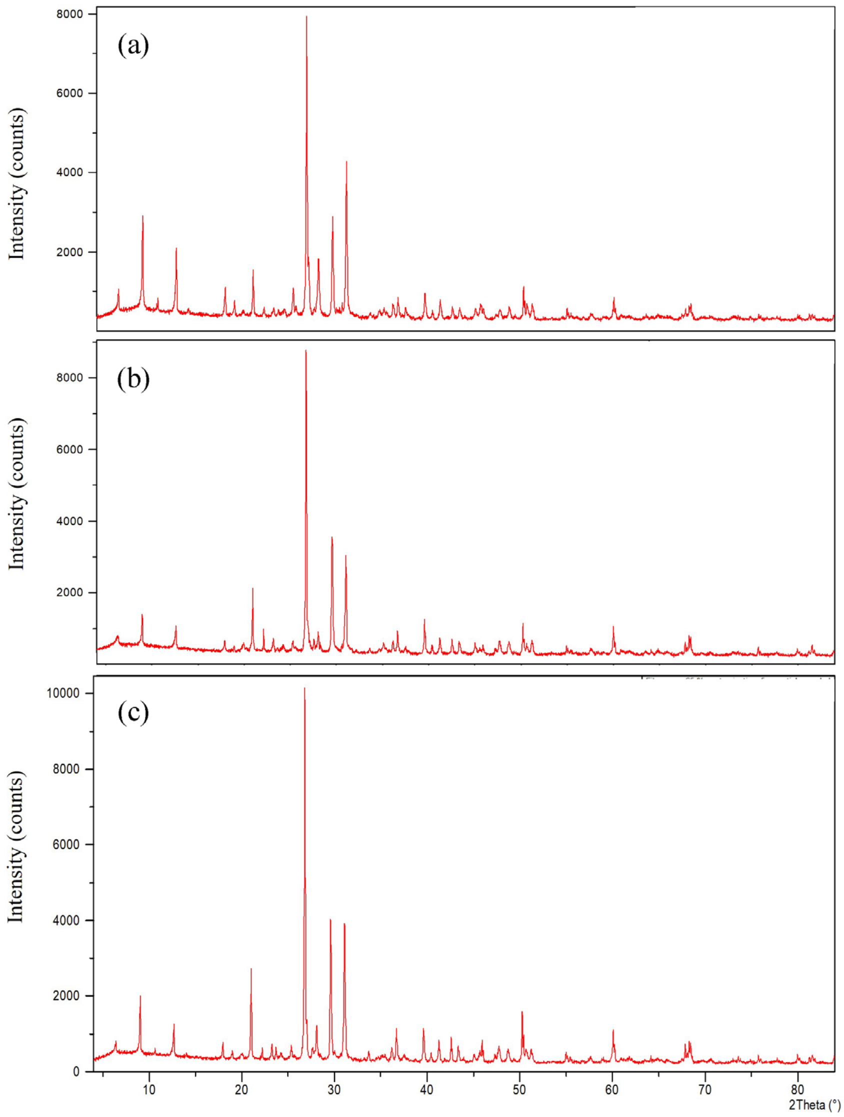

Fig. 4 XRD results (a) clean soil, (b) 5% contamination, (c) 15% contamination

paths explains the enhanced permeability, while the initial formation of new mineral phases, particularly clay minerals detected in the XRD, accounts for the increased cohesion.

The 15% contamination level emerges as a critical threshold marking a fundamental transition in soil behavior. At this concentration, the soil experiences a dramatic reduction in hydraulic conductivity (93.5% reduction) coinciding with significant changes in shear strength parameters, including a 16.4% reduction in friction angle and a 151.5% increase in cohesion. XRD analysis reveals maximum alteration of carbonate minerals at this concentration. These microstructural modifications provide the physical mechanism for both the increased cohesion and reduced friction angle, creating a more integrated soil fabric through particle surface modification and the development of connecting mineral phases. This transitional point represents a shift from granular to cohesive soil behavior, evidenced by both hydraulic and shear responses.

At higher contamination levels (20%), the soil undergoes extensive structural modification. SEM analysis reveals (Fig. 5) the development of a denser fabric structure with extensive particle surface modifications, explaining the dramatic reduction in hydraulic conductivity (98.7% reduction). The transition from an open structure to a more compacted fabric with extensive particle bridges corresponds with findings by Shariatmadari et al. [25], who observed similar structural evolution in contaminated soils and linked it to enhanced cohesion development. The formation of fibrous, needle-like crystals, observed in SEM imaging (Fig. 5(i)-(h)), creates extensive particle connections and matrix densification. The formation of fibrous, needle-like crystals is consistent with observations by Sunil et al. [22], who identified comparable secondary mineral formations in contaminated soils, particularly at higher contamination levels. These microstructural changes correspond with complex mechanical behavior, including sustained cohesion enhancement (reaching 144.7% increase at 20% contamination) and continued friction angle reduction. The development of these new mineral bridges provides the physical mechanism for both the increased cohesion and reduced permeability. The extensive structural modifications observed at higher contamination levels provide physical confirmation of the complex strength evolution patterns, corresponding with observations by Arasan [40].

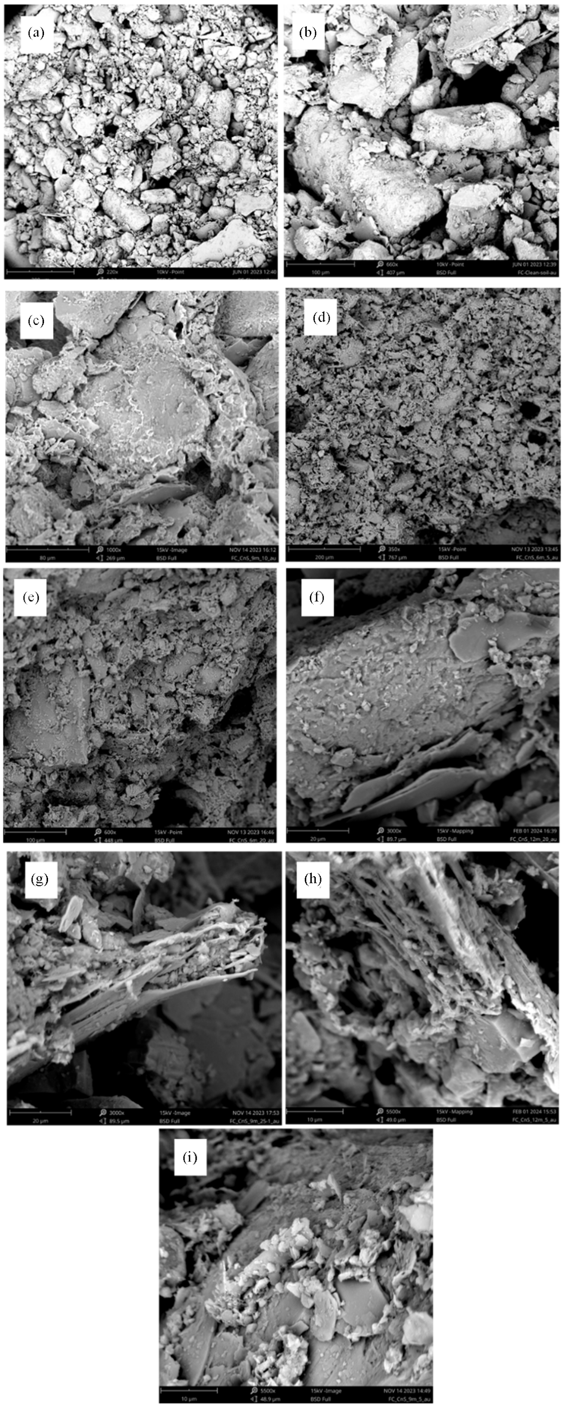

Fig. 5 SEM images: clean soil general aspect (a) x220, (b) x600; (c) 9 months 10% contaminated soil particle alteration (x1000); 6 months 5% contaminated soil general aspect (d) x350, (e) x600; (f) 12 months 20% contaminated soil particle alteration (x3000); contaminated soil new mineral formation (g) x3000, (h) x5500, (i) x5500

The temporal evolution of soil properties reveals an interesting contrast between hydraulic and shear strength pameters. While hydraulic conductivity demonstrates time-independence, maintaining stable values throughout the 12-month period for each contamination level, shear strength parameters show continued evolution. This difference suggests that structural modifications affecting permeability occur rapidly upon initial exposure, while mechanical property changes involve ongoing mineralogical transformations. The relationship between fabric modification and permeability properties observed in this study parallels the work of Oztoprak and Pisirici [24], who documented comparable structure-property relationships through SEM analysis. For the shear parameters, the immediate response in the first three months suggests rapid initial reactions between leachate components and soil minerals. The continued evolution during the medium-term period (3-6 months) indicates ongoing mineralogical transformations, while the long-term behavior reveals the permanent nature of these modifications. This pattern of sustained parameter changes, particularly the continued reduction in friction angle and variable cohesion response, suggests that leachate contamination induces lasting alterations to soil fabric and mineralogy. These observations align with previous research, including studies by Sunil et al. [22] and Shariatmadari et al. [25], who documented similar patterns of structural evolution in contaminated soils.

The formation of new mineral phases, particularly secondary clay minerals and aluminum silicate hydrates confirmed by XRD analysis, explains the complex modifications in both hydraulic and mechanical properties. the transformation of existing minerals, evidenced by XRD peak shifts, contributes to the strengthening effect while simultaneously reducing permeability. These mineralogical changes correspond with findings by Kumar et al. [38] and Khodary et al. [31], who reported similar property modifications in contaminated silty clays.

The relationship between fabric modification and engineering properties observed in this study demonstrates how microstructural changes serve as the underlying mechanism for both hydraulic and shear strength property evolution.

6 Conclusions

The research investigated the evolution of soil hydraulic conductivity and shear strength parameters under leachate contamination through permeability tests and direct shear tests conducted over a 12-month period on sandy clayey silt soil subjected to various degrees of contamination (5-25%). The key findings are concluded as:

Hydraulic conductivity modifications are primarily governed by contamination level rather than exposure duration:

- Permeability values remained stable throughout the testing period, indicating rapid establishment of new structural configurations upon initial exposure.
- A critical threshold at 15% contamination marks the transition from granular to cohesive soil behavior. Below this threshold (5-10%), increased permeability (up to 1.2E-7 m/s) indicates enhanced hydraulic transmission, while higher contamination levels show significant reductions. This behavioral shift coincides with mineralogical alterations and microstructural modifications, evidenced by the formation of new mineral phases and development of particle bridges.

Friction angle modifications demonstrate time-independent behavior characterized by:

- An immediate and consistent reduction upon leachate exposure, with values decreasing from 36.5° to 31-31.5° (13.7-15.1% reduction).
- Remarkable stability throughout the testing period, maintaining values within ±2° of initial reduction regardless of contamination level.
- Maximum reduction occurring at 15% contamination (16.4% reduction), indicating a critical threshold in soil response.

Cohesion evolution exhibits time-dependent behavior marked by:

- A distinct three-phase pattern: initial increase (0-3 months), peak development (6 months), and gradual degradation (6-12 months).
- Maximum enhancement occurring between 15-20% contamination levels, with peak values reaching up to 151.5% increase from initial values.
- Consistent behavior pattern across all contamination levels, though with varying intensities.
- Systematic increase in peak-residual differences with both contamination level and time.

These findings provide quantitative parameters for waste containment facility design and offer a framework for assessing long-term contamination effects on soil properties. The identified behavioral threshold at 15% contamination serves as a critical reference point for engineering design and risk assessment. Future research should address the reversibility of these modifications under various environmental conditions and the influence of different leachate compositions on soil property evolution.

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