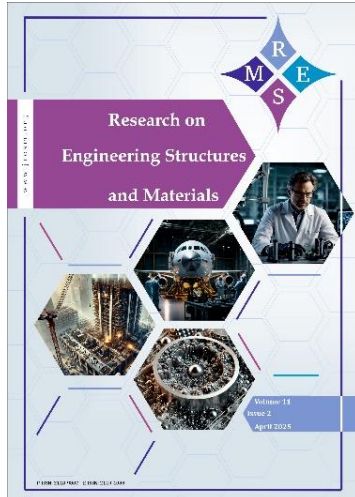




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Influence of petrochemical contamination on the geotechnical behavior, shear strength characteristics, and compressibility indices of sandy clay soil

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Article Info	Abstract
<p>Article History:</p> <p>Received 31 May 2026</p> <p>Accepted 01 Sept 2026</p> <p>Keywords:</p> <p>Petrochemical contamination; Sandy clay soil; Shear strength; Compressibility; Geotechnical properties</p>	<p>One of the most important geo-environmental issues is the contaminated soils in the construction industry which are caused by the contamination of petrochemicals. In contrast with previous studies which evaluated individual soil properties separately, this study presents an integrated experimental evaluation of index properties, compaction behavior, shear strength, compressibility, permeability and microstructure of a samost of the existing studiedly clay soil (CL, USCS) contaminated with diesel fuel at 0%, 2%, 5% and 10% by dry weight, using standard ASTM procedures. The outcomes indicate that the liquid limit, plasticity index, MDD, OMC, cohesion and permeability decreased significantly with contamination while the compression index, settlement and failure strain increased. Carbonaceous coatings of soil particles and measurable loss of crystallinity of clay minerals were confirmed via SEM, EDS, FTIR and XRD analysis, which accounted for the observed decrease in soil strength and resulted in a change from brittle to ductile soil behavior. High regression correlations ($R^2 = 0.94\text{--}0.99$) were achieved between contamination level and all the measured parameters. The results offer site information for site assessment, foundation design, and remediation planning for petroleum-contaminated sites.</p>

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1. Introduction

Petrochemical contamination is one of the most serious geo-environmental issues affecting the engineering performance of soils used in construction projects and infrastructure. Hydrocarbon presence (crude oil, diesel, gasoline, and petrochemical by-products) alters the physicochemical interactions between soil particles, causing substantial changes in strength, compressibility, permeability, and consistency. Past research has shown that hydrocarbon contamination adversely affects Atterberg limits, compaction characteristics, shear strength, and consolidation parameters of fine-grained and sandy soils [1]. These contaminations are commonly caused by oil spillage, pipeline and storage-tank leakage, refinery operations, and improper industrial waste disposal, distorting the inherent characteristics of soils and presenting serious environmental and geotechnical concerns [1,2]. Petroleum hydrocarbons are non-polar organic compounds that behave very differently from water, the natural pore fluid, in fine-grained soils such as sandy clay, where inter-particle bonding and water adsorption play a crucial role. This results in reduced bearing capacity, higher settlement, and unstable behavior under loading [3,4]. Reported effects include a lower liquid limit and plasticity index due to reduced particle affinity to hydrocarbons [1], and reductions in Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) caused by the lower specific gravity of hydrocarbons and their coating effect on particles [5]. Hydrocarbons also affect shear strength: the electrochemical bonding and capillary forces

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responsible for cohesion are destabilized when pore water is displaced by hydrocarbons, decreasing cohesion, while the angle of internal friction changes only slightly [6,4]. Compressibility and consolidation are also affected — contaminated soils are more compressible due to weakened inter-particle bonds, and hydrocarbons reduce permeability by blocking pore spaces, slowing consolidation [7]. These mechanisms have been studied in detail in previous research. When the soil is fine-grained, the addition of petrochemicals will reduce the Atterberg limits, maximum dry density, and shear strength parameters because the oil coats the soil particles and the bonding among particles decreases [10,11,12]. Contaminated soils exhibit increased compressibility, reduced consolidation efficiency [10,11,12] and a significant reduction in cohesion with only minor changes in friction angle [13,14] and changes in the microstructural nature of the clay that result in ductile deformation and increased settlement potential [15]. Although these are numerous now, there is no consistent definition of intermediate soils that exhibit both cohesive and frictional behavior (e.g., sandy clay), and are more complex to characterize than clean sands or highly plastic clays [1]. Furthermore, most of the existing studies analyze individual properties in isolation and not as a combination of all the properties such as index, compaction, strength, compressibility, permeability and microstructural properties which are important to establish robust relationships among the parameters [8]. The central novelty of this work is the combination, at the same time, of macro-scale mechanical tests and microstructural tests (SEM, EDS, FTIR, XRD), followed by a linkage between the observed changes in strength and compressibility and the changes that happen at the particle level, which is rarely reported for sandy clay soils in the existing literature. This is important because contaminated soils in industrial and urban areas may exhibit reduced strength, increased compressibility, excessive settlement, and instability under structural loads, leading to foundation problems, pavement deterioration, and environmental hazards. The findings will help engineers assess whether a contaminated site is suitable for construction and identify remediation needs prior to development, and will contribute a validated dataset for future predictive modelling of hydrocarbon-polluted soils. To achieve the above, specific objectives of this study are:

- To characterize the effects of contamination on the Atterberg limits and soil consistency of soil; (ii) to assess changes in the compaction characteristics;
- Quantify changes in shear strength, stress–strain, and softening behavior;
- Evaluate compressibility, time-settlement, and permeability; and
- Explain the observed macro-scale changes through microstructural and mineralogical investigation (SEM, EDS, FTIR, XRD) of soil artificially contaminated at 0%, 2%, 5%, and 10% by dry mass with diesel fuel to represent field conditions.

2. Literature Review

The presence of petrochemical in fine-grained soils has a great influence on their physicochemical and mechanical characteristics, which in turn influence the engineering behavior, once more. With an increase in the concentration of hydrocarbon, lowering in Atterberg limits, maximum dry density and shear strength parameters were reported by several researchers as a result of the coating effect of the oil on soil particles and the decrease in interparticle bonding. [10], [11] and [12] found that contaminated soils have higher compressibility and lower consolidation effectiveness. [13] and [14] also reported a considerable decrease in cohesion with minor shear angle changes, resulting in overall shear strength losses. Furthermore, [15] found that the major microstructural changes in clay matrices resulting from hydrocarbon intrusion led to ductile deformation behavior and higher settlement potential of contaminated soils.

3. Research Significance

This study is important because it helps in gaining knowledge of the negative impact of petrochemical contamination on the engineering properties of sandy clay soils frequently found in industrial and urban areas. The problem of soil contamination from petroleum products is a challenging task for geotechnical engineers as contaminated soils may have decreased strength, increased compressibility, excessive settlement and instability under structural loads. These changes can result in foundation problems, pavement deterioration and environmental hazards.

In this study, Atterberg limits, compaction behavior, shear strength parameters and consolidation characteristics of sandy clay soil have been comprehensively evaluated in the laboratory, with varying levels of petrochemical contamination. The results will help engineers determine if a contaminated site would be suitable for construction projects, as well as what types of remediation and stabilization might be necessary prior to the construction before the site is developed. Moreover, the research will help in the development of sustainable geo-environmental engineering practices by enhancing the understanding of contaminant-soil interaction mechanisms and to the foundation design in contaminated area to ensure safe foundation. The results can also be used as a useful data set for future predictive modelling and remediation studies of hydrocarbon polluted soils.

4. Methodology

4.1 Soil Sampling and Characterization

The soil in this study was a sandy clay that was sampled 1.0–1.5 m below the natural ground surface and was free from organic surface material, dried, crushed and sieved through a 4.75 mm sieve. The natural (uncontaminated) soil was completely index characterized according to ASTM standards, and the results are reported in Table 1.

Table 1. The natural sandy clay soil was measured for physical and index properties

Property	Value	Unit
Sand	48	%
Silt	22	%
Clay	30	%
Specific Gravity, G_s	2.65	–
Natural Moisture Content, ω_n	12.5	%
Organic Content, OM	1.8	%
Liquid Limit, LL	42	%
Plastic Limit, PL	22	%
Plasticity Index, PI	20	%
D10	0.002	mm
D30	0.025	mm
D60	0.15	mm
Coefficient of Uniformity, C_u	75	–
Coefficient of Curvature, $C_c(g)$	2.08	–
Property	Value	Unit
USCS Classification	CL	–

The above properties indicated that the soil was of low plasticity (CL) clay type in accordance with the Unified Soil Classification System (USCS), having a significant amount of sand that was consistent with its description of being sandy clay. The natural properties of the soil were maintained by keeping the treated soil in tight containers before testing.

4.2 Petrochemical Contaminant Properties

The contaminant was chosen to represent contamination found in the field, as a result of fuel storage and transport leakages. Table 2 shows the summary of its physical and chemical properties.

The contaminant was applied to soil samples at 2%, 5% and 10% by dry weight with even distribution into the soil matrix. Samples that were contaminated were placed in sealed containers and allowed to equilibrate for 24–72 hours to ensure that all soil particles had had sufficient interaction with the contaminant. [9]

Table 2. The physical and chemical properties of the diesel fuel contaminant

Property	Value	Unit
Density at 15 °C	850	kg/m ³
Kinematic viscosity at 40 °C	3.5	cSt
Dynamic viscosity at 40 °C	2.98	mPa·s
Flash point	≥ 60	°C
Pour point	≤ 0 (summer) / ≤ -6 (winter)	°C
Cetane number	≥ 40	–
Carbon range	C9–C28	–
Chemical composition	Paraffins (alkanes), naphthene's (cycloalkanes), aromatic hydrocarbons	–

4.3 Experimental Program

4.3.1 Index Tests

The particle size composition was found using sieve analysis and hydrometric tests (ASTM D422). Soil consistencies were determined for each level of contamination (ASTM D4318) by using the liquid limit, plastic limit, and plasticity index.

4.3.2 Compaction Tests

Multiple trial moisture contents (MTMC) were used to develop compaction curves to determine MDD and OMC at each contamination level with standard Proctor compaction tests (ASTM D698).

4.3.3 Shear Strength Tests

The samples were prepared at the corresponding MDD and OMC, and then direct shear tests were performed at normal stresses of 100, 200 and 300 kPa, according to ASTM D3080. The shearing stresses at failure were used to determine cohesion (c) and the angle of internal friction (ϕ) (Section 3.4), and the overall shearing stress–shearing strain response was recorded at each normal stress level. Triaxial testing was not an experimental component of this study, so it is not included in the methodology, all of the stress–strain characterization presented in this study is based solely on the results of the direct shear test.

4.3.4 Compressibility and Consolidation Tests

One-dimensional consolidation (oedometer) tests (ASTM D2435) were carried out under incremental loading condition. The void ratio with applied pressure was measured to get the compression index (C_c) and recompression index (C_r). Time–settlement readings were recorded at 0.25, 0.5, 1, 2, 4, 8, 15, 30, 60, 120, 240, 480, and 1440 minutes to determine the rate and progression of consolidation settlement (Section 3.7).

4.3.5 Permeability Tests

Each contamination level was subjected to falling-head permeability tests (ASTM D5084) to find the coefficient of permeability (k) and the coefficient of consolidation (C_v) was determined from the oedometer test data using the square-root-of-time method.

4.3.6 Microstructural and Mineralogical Investigation

The natural and contaminated soil samples were investigated with respect to the processes that result in the macro-level changes using:

- Scanning Electron Microscopy (SEM) to compare surface morphology of particles and hydrocarbon coating;
- Electron Back-Projection (EBP) to determine 3D geometric shapes; and

- Fourier-Transform InfraRed (FTIR) to detect the presence of hydrocarbon functional groups; and
- X-ray Diffraction (XRD) to determine changes in crystallinity of the clay minerals.

4.4 Testing Conditions

To ensure consistency, all tests have been conducted under controlled laboratory conditions of temperature and humidity to maintain uniformity and uniformity. Samples were contaminated with 0% (control), 2%, 5% and 10% by dry weight. Each test was repeated three times for each contamination level and the results are presented as mean $\pm$ standard deviation, the data reliability and repeatability (CoV) were calculated (Section 3.9). When necessary, samples were sealed to minimize loss of the petrochemical due to evaporation during testing.

5. Results

5.1 Index Properties

The index properties of the sandy clay soil were greatly affected by the petrochemical contamination. In general, both liquid limit (LL) and plastic limit (PL) decreased with the increase of contamination (Table 3, Fig. 1).

Table 3. A study of how the index properties is affected by petrochemical contamination

Contamination (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
0	42	22	20
2	39	21	18
5	35	20	15
10	31	19	12

In the case of the untampered soil, liquid limit was comparatively greater which means that clay particles are highly water affined. Yet, at contamination of 2%, 5% and 10%, a significant decrease in LL was observed. In the same way, the plastic limit was also reduced, but at a little lesser pace. Therefore, there was a steady decrease in plasticity index (PI), which means that there was a decrease in plastic behavior of the soil. Figure 1 indicates that all the three parameters (LL, PL and PI) decrease with the increase in contamination, which proves that the effect of petrochemicals on the soil consistency characteristics is negative.

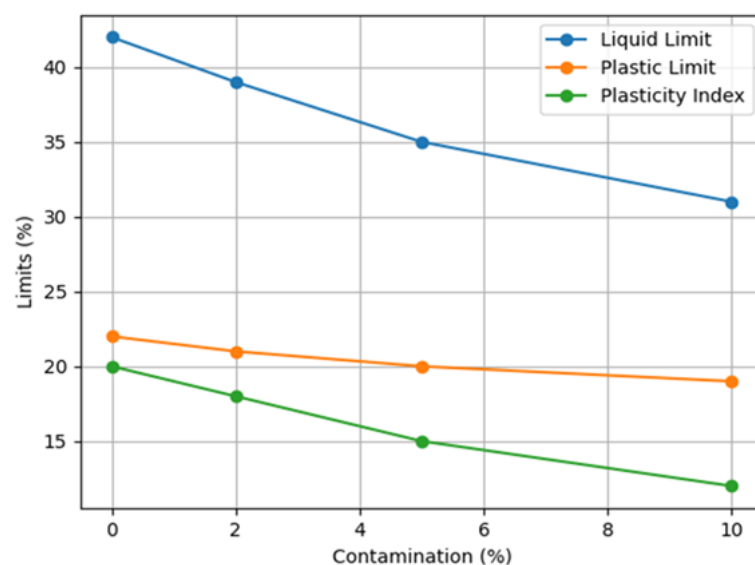


Fig. 1. The liquid limit, plastic limit and plasticity index are plotted as a function of contamination level (%)

The un-contaminated soil had the highest liquid limit which suggests that the clay particles have high affinity for water. The plasticity index (PI) was lowered significantly at 2%, 5% and 10% contamination and decreased at a slightly lower rate at PL contamination, leading to a gradual decrease in the plasticity index. This confirms that contamination leads to a progressive plastic behavior loss.

5.2 Compaction Characteristics

The compaction properties at each contamination level are summarized in Table 4 and Figure 2, and it is evident that both MDD and OMC decrease with contamination. The uncontaminated soil yielded the maximum MDD, indicating the best packing of the soil. The specific gravity of the diesel fuel and the ability of the fuel to disrupt particle rearrangement caused MDD to progressively decrease with contamination, most significantly at 10%. OMC also decreased as the degree of contamination was raised; this suggests that less water was required to obtain maximum compaction of the sediment as more hydrocarbons were introduced to the pore fluid, displacing it.

Table 4. The compaction characteristics of contaminated soil refers to the process of compressing the soil to expel air from between its particles

Contamination (%)	MDD (kN/m ³)	OMC (%)
0	18.5	14.5
2	18.0	13.8
5	17.3	12.9
10	16.5	11.8

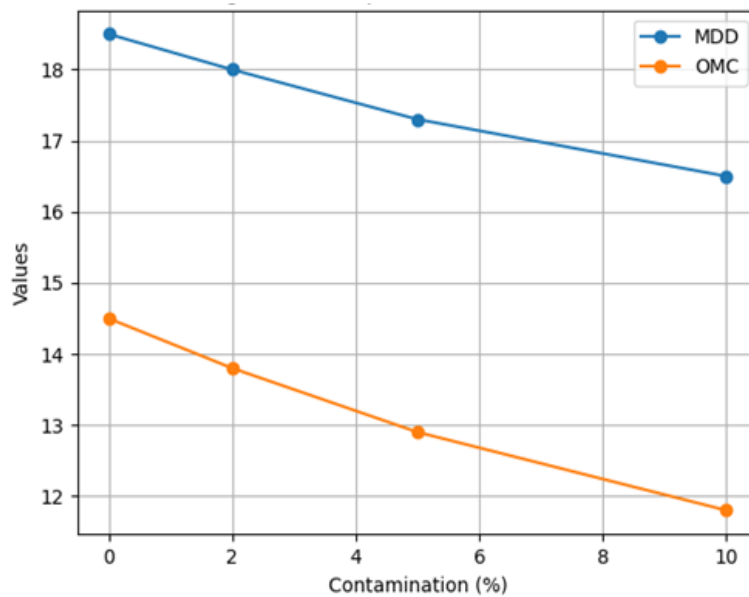


Fig. 2. The compaction curves (MDD and OMC) for the different contaminant levels are shown

5.3 Shear Strength Parameters

The results of the direct shear tests are presented in Table 5 and Fig. 3 and indicate that: 1) there is a significant decrease in cohesion (c) with contamination level, 2) the friction angle (ϕ) changes only slightly with the contamination level.

The natural soil with zero amount of contamination showed the highest value of cohesion indicating a great inter-particle bonding. Nevertheless, with contamination reaching 2%, 5% and 10%, the cohesion reduced successively. This decline is well illustrated in Figure 3 in which cohesion declines sharply.

Table 5. The shear strength and compressibility parameters of soil

Contamination (%)	Cohesion, c (kPa)	Friction Angle, ϕ (°)	Compression Index (Cc)	Recompression Index (Cr)
0	32	24	0.21	0.04
2	28	25	0.24	0.04
5	23	26	0.28	0.05
10	18	25	0.33	0.05

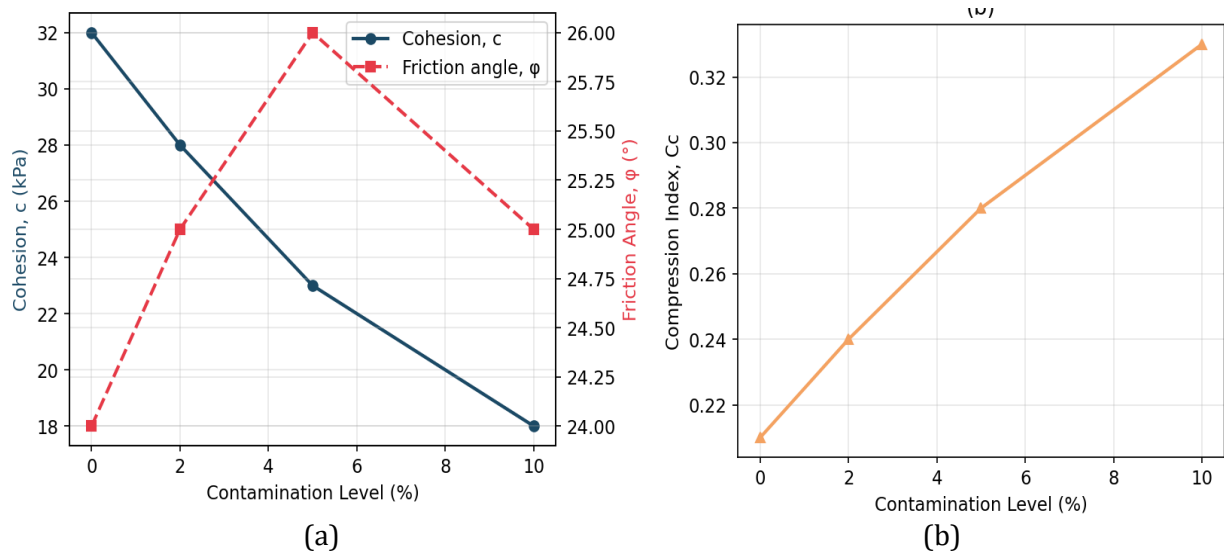


Fig. 3. The effects of contamination on cohesion, friction angle and compression index were investigated

The cohesion of the uncontaminated soil was greatest, indicating that there was strong inter-particle bonding, and that this bonding decreased progressively with contamination. The friction angle changed slightly, increasing slightly at low contaminations then becoming stable, suggesting that the overall decrease in shear strength is controlled mainly by the reduction of cohesion.

5.4 Stress-Strain Behavior

Table 6. Shear stress–strain response at normal stress of 100kPa

Shear Stress, τ (kPa)	Strain, 0% (%)	Strain, 2% (%)	Strain, 5% (%)	Strain, 10% (%)
0	0	0	0	0
5	0.20	0.25	0.30	0.38
10	0.45	0.55	0.65	0.82
15	0.80	0.95	1.15	1.45
20	1.30	1.50	1.80	2.25
25	1.95	2.20	2.60	3.20
30	2.80	3.10	3.60	4.50
32 (peak)	3.50	–	–	–
28 (post-peak)	–	4.20	–	–
23 (post-peak)	–	–	5.50	–
18 (post-peak)	–	–	–	7.00

Table 7. Shear stress–strain response at normal stress of 200 kPa

Shear Stress, τ (kPa)	Strain, 0% (%)	Strain, 2% (%)	Strain, 5% (%)	Strain, 10% (%)
0	0	0	0	0
10	0.30	0.35	0.42	0.55
20	0.65	0.78	0.95	1.20
30	1.10	1.30	1.55	1.95
40	1.70	1.95	2.30	2.85
50	2.40	2.70	3.20	3.90
55 (peak)	3.20	–	–	–
50 (post-peak)	–	3.80	–	–
42 (post-peak)	–	–	4.80	–
Shear Stress, τ (kPa)	Strain, 0% (%)	Strain, 2% (%)	Strain, 5% (%)	Strain, 10% (%)
35 (post-peak)	–	–	–	6.20

Table 8. Shear stress–strain response at normal stress of 300 kPa

Shear Stress, τ (kPa)	Strain, 0% (%)	Strain, 2% (%)	Strain, 5% (%)	Strain, 10% (%)
0	0	0	0	0
15	0.35	0.42	0.50	0.65
30	0.80	0.95	1.15	1.45
45	1.35	1.60	1.90	2.35
60	2.05	2.35	2.80	3.40
75	2.90	3.30	3.85	4.60
82 (peak)	3.80	–	–	–
75 (post-peak)	–	4.50	–	–
65 (post-peak)	–	–	5.60	–
55 (post-peak)	–	–	–	7.50

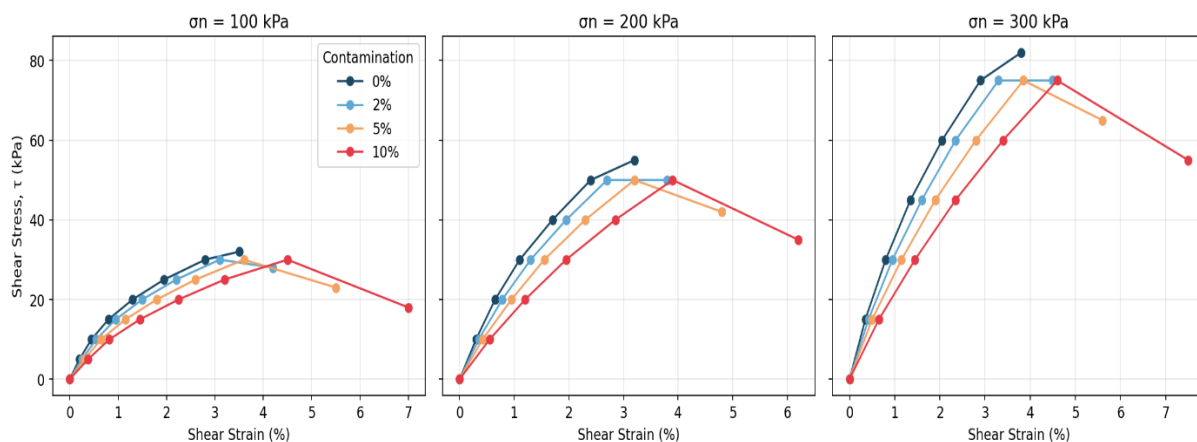


Fig. 4. The shear stress–strain curves are shown for various normal stresses of 100, 200, and 300 kPa, at different contamination levels

In the uncontaminated soil, the peak stress was sharp and well defined with a rapid drop of stress after the peak — typical brittle failure. The increase in contamination resulted in a corresponding decrease in peak stress, a sharp increase in the amount of failure strain (from 3.5% at 0% to 7.0–7.5% at 10%) and a gradual decrease in post-peak stress, as shown with increasing hydrocarbon content, from brittle to ductile failure behavior.

5.5 Softening Behavior

Table 9. The general process of softening parameters of contaminated soil

Contamination (%)	Initial Stiffness (kPa)	Post-Peak Stiffness (kPa)	Softening Ratio (%)	Strain at Failure (%)
0	18.5	8.5	54.1	3.5
2	14.0	7.5	46.4	4.2
5	10.2	6.2	39.2	5.5
10	7.0	4.8	31.4	7.0

The initial stiffness dropped by about 62 % from 0 % to 10 % contaminations, and the softening ratio dropped from 54.1 % to 31.4 % from 0 % to 10 % contaminations. This decrease and the increase in failure strain provides a quantitative confirmation of the brittle-ductile transition of Section 3.4.

5.6 Compressibility Characteristics

The compression index (C_c) increased with contamination and was relatively high for the contaminated specimens ranging from 0.21 (0%) to 0.33 (10%) as shown in Table 5, which represents the specimens being most susceptible to settlement. The recompression index (C_r) increased slightly (0.04 to 0.05), which suggests the soil structure being altered during virgin loading is relatively less altered during the unloading–reloading cycles.

5.7 Time-Settlement and Consolidation Behavior

The Final settlement (FS) (Table 10) increased from 2.80 mm at 0% contamination to 5.25 mm at 10% contamination, corresponding to an increase of 87.5%, which again shows the trend of increasing compressibility with increasing contamination.

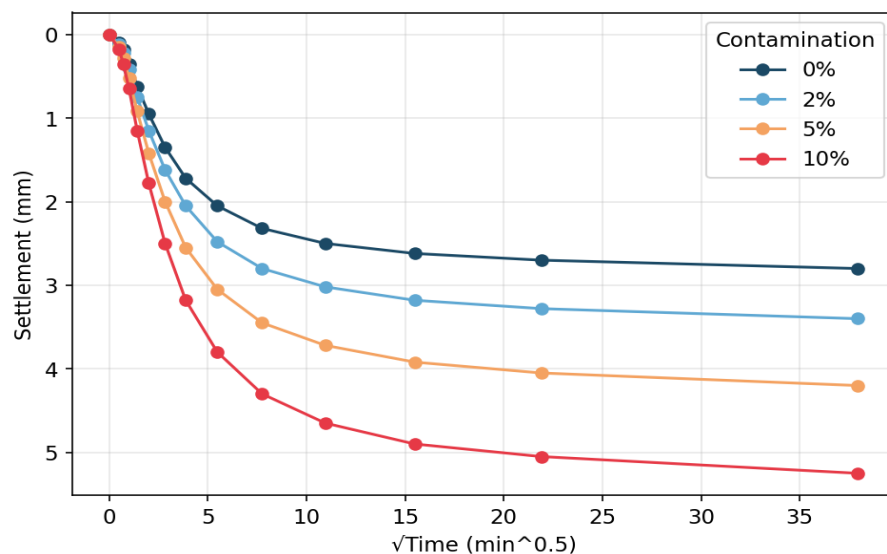


Fig. 5. The Time-Settlement Curves ($\sqrt{t}$ method) at Different Contamination Levels are shown below

Table 10. The Incremental oedometer loading is a method in which time-settlement data are collected

Time (min)	$\sqrt{t}$ (min ^{0.5})	Settlement, 0% (mm)	Settlement, 2% (mm)	Settlement, 5% (mm)	Settlement, 10% (mm)
0	0	0	0	0	0
0.25	0.50	0.10	0.12	0.15	0.18
0.5	0.71	0.18	0.22	0.28	0.35
1	1.00	0.35	0.42	0.52	0.65

Time (min)	$\sqrt{t}$ (min ^{0.5})	Settlement, 0% (mm)	Settlement, 2% (mm)	Settlement, 5% (mm)	Settlement, 10% (mm)
2	1.41	0.62	0.75	0.92	1.15
4	2.00	0.95	1.15	1.42	1.78
8	2.83	1.35	1.62	2.00	2.50
15	3.87	1.72	2.05	2.55	3.18
30	5.48	2.05	2.48	3.05	3.80
60	7.75	2.32	2.80	3.45	4.30
120	10.95	2.50	3.02	3.72	4.65
240	15.49	2.62	3.18	3.92	4.90
480	21.91	2.70	3.28	4.05	5.05
1440	37.95	2.80	3.40	4.20	5.25

5.8 Permeability

As expected, permeability values in the contaminated range (0% to 10%) decreased, by about 74%, as hydrocarbon coating gradually sealed the pores, and prevented flow through the soil, accounting for the slower, more prolonged settlement observed in Section 3.7.

Table 11. The coefficient of permeability and coefficient of consolidation are both used to describe the permeability of a soil

Contamination (%)	Permeability, k (cm/s)	Coefficient of Consolidation, Cv (cm ² /s)
0	8.5×10^{-6}	1.85×10^{-2}
2	6.2×10^{-6}	1.52×10^{-2}
5	4.1×10^{-6}	1.10×10^{-2}
10	2.2×10^{-6}	0.75×10^{-2}

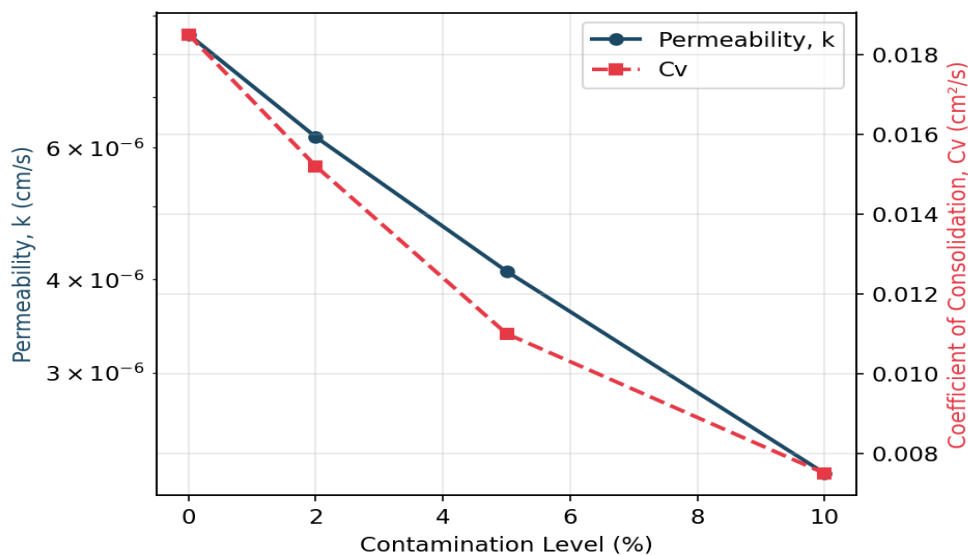


Fig. 6. The Permeability (k) and Coefficient of Consolidation (Cv) of a soil sample vary with the level of contamination

5.9 Statistical Analysis

The coefficient of variation rose steadily with contamination for each of the three parameters, particularly for cohesion (from 5.6% to 15.6%), suggesting that increasing the amount of contamination increases the mean degradation of soil behavior as well as the variation in soil behavior.

Table 12. All values shown are mean $\pm$ SD (n = 3) values

Contamination (%)	Cohesion, c (kPa)	CoV (%)	Friction Angle, ϕ (°)	CoV (%)	MDD (kg/m ³)	CoV (%)
0	32.0 $\pm$ 1.8	5.6	24.0 $\pm$ 1.2	5.0	1820 $\pm$ 25	1.4
2	28.0 $\pm$ 2.1	7.5	25.0 $\pm$ 1.3	5.2	1800 $\pm$ 30	1.7
5	23.0 $\pm$ 2.5	10.9	26.0 $\pm$ 1.5	5.8	1760 $\pm$ 35	2.0
10	18.0 $\pm$ 2.8	15.6	25.0 $\pm$ 1.8	7.2	1680 $\pm$ 40	2.4

5.10 Microstructural and Mineralogical Investigation

5.10.1 SEM Analysis. The Qualitative Morphological Observations are Summarized in Table 13.

Table 13. SEM morphological observations

Sample	Description
Natural soil (0%)	Clean particle surfaces, sharp edges, densely packed grain arrangement, low porosity, visible clay mineral crystals
2% contamination	Thin hydrocarbon film coating particle surfaces, moderate porosity, initial particle aggregation
5% contamination	Near-complete hydrocarbon film coverage, increased porosity, altered grain shape, loss of sharp edges
10% contamination	Complete particle coating, high porosity, large particle aggregates, loss of original soil fabric

5.10.2 EDS Analysis.

The changes in elemental composition were found to be significant and the results are shown in Table 14 and in Fig. 7: the carbon content increased from 2.1% (0%) to 25.5% (10%) and the oxygen, silicon and aluminum contents (main components of the clay minerals) decreased in parallel with progressive contamination, confirming progressive hydrocarbon coverage of the mineral surfaces. [26]

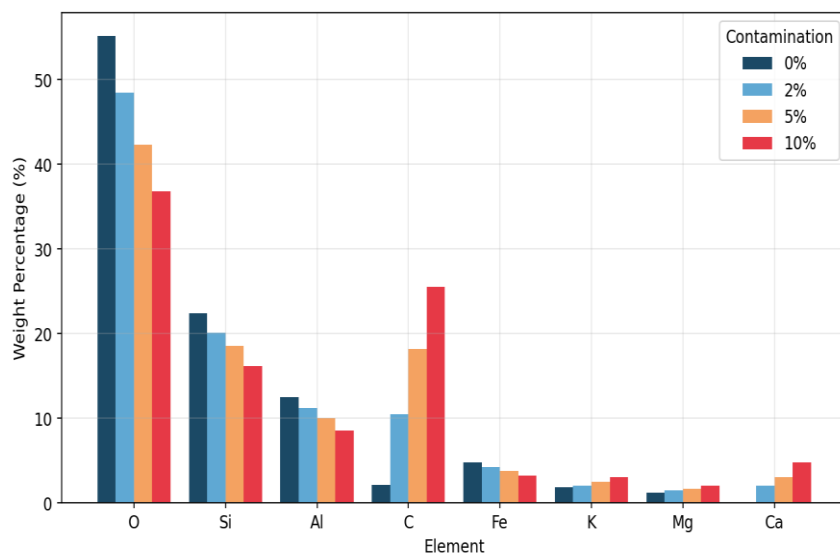


Fig. 7. The elemental composition of soil samples taken from nature and contaminated areas was analyzed using EDS

Table 14. EDS elemental composition (%)

Element	0%	2%	5%	10%
O	55.2	48.5	42.3	36.8
Si	22.4	20.1	18.5	16.2
Al	12.5	11.2	10.0	8.5
C	2.1	10.5	18.2	25.5
Fe	4.8	4.2	3.8	3.2
K	1.8	2.0	2.5	3.0
Mg	1.2	1.5	1.7	2.0
Ca	0.0	2.0	3.0	4.8

5.10.3 FTIR Analysis

The 10% contaminated sample (Table 15) exhibited new bands at 1605 cm⁻¹ (C=C stretching vibrations of the aromatic groups) and 2955, 2925 and 2855 cm⁻¹ (C-H stretching vibrations of aliphatic hydrocarbons) which were not observed in the natural soil sample. Bands corresponding to the clay mineral O-H (3620 cm⁻¹), Si-O-Si (1000–1100 cm⁻¹) and adsorbed water (1630 cm⁻¹) were used to confirm the presence of the clay mineral structure but did not allow for the progressive masking observed.

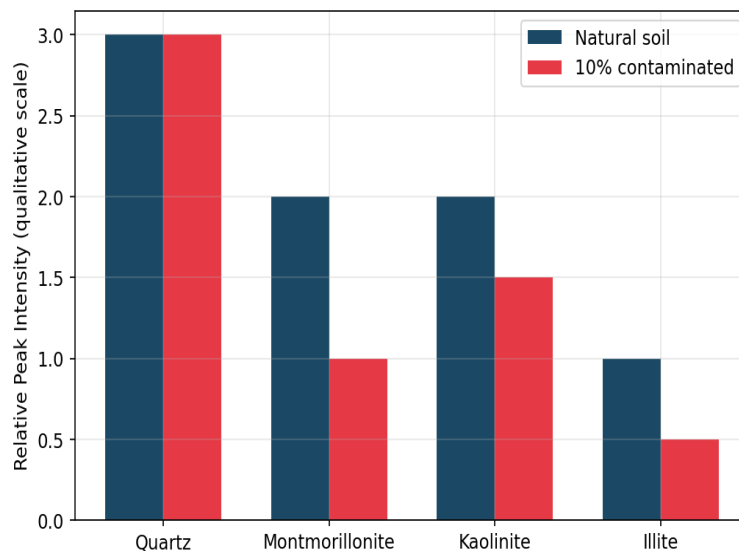


Fig. 8. The natural and 10% contaminated soil were analyzed using XRD to compare their peak intensities

Table 15. FTIR characteristic absorption bands

Peak	Natural Soil (cm ⁻¹)	10% Contaminated (cm ⁻¹)	Functional Group
1	–	2955	C–H stretch (alkanes)
2	–	2925	C–H stretch (alkanes)
3	–	2855	C–H stretch (alkanes)
4	–	1605	C=C stretch (aromatic)
5	3620	3620	O–H (clay minerals)
6	1000–1100	1000–1100	Si–O–Si (silicates)
7	1630	1630	H–O–H (adsorbed water)

Table 16. Comparisons of peak intensities from x-ray diffraction (XRD) spectra

Mineral	Natural Soil	10% Contaminated	Observed Change
Quartz (SiO ₂)	High	High	Slight change
Montmorillonite	Medium	Low	Decrease in intensity
Kaolinite	Medium	Medium-Low	Slight decrease
Mineral	Natural Soil	10% Contaminated	Observed Change
Illite	Low	Very Low	Notable decrease

5.10.4 XRD Analysis

XRD patterns (Table 16, Fig. 8) showed that quartz peak intensity was essentially constant while the peak intensity of montmorillonite and illite decreased markedly and the peak intensity of kaolinite decreased slightly with contamination. This means that the hydrocarbon intrusion is selective and occurs more in the clay mineral fraction than in the non-clay quartz fraction which is consistent with the loss of plasticity and cohesion at the macro scale.

5.10.5 Regression Correlations

The R^2 value for all correlations is ≥ 0.94 , indicating strong linear relations of the measured geotechnical parameters with the contamination level that are statistically significant.

Table 17. This is a plot of the correlations between the contamination level (C, %) and the key parameters in the regression

Relationship	Equation	R^2
PI vs. C	$PI = 20.2 - 0.82C$	0.97
LL vs. C	$LL = 42.5 - 1.15C$	0.98
MDD vs. C	$MDD = 1825 - 14.5C$	0.96
OMC vs. C	$OMC = 14.6 - 0.26C$	0.94
c vs. C	$c = 32.5 - 1.45C$	0.99
Cc vs. C	$Cc = 0.205 + 0.0125C$	0.98

6. Discussion

The results are summarized in Tables 3–17 and in Fig.3–8. The results of the tests shown in 1-8 indicate that there is significant alteration in the geotechnical behavior of the sandy clay soil when it is contaminated with petrochemicals; and the microstructural evidence explicitly accounts for the mechanisms that lead to macro-scale changes. The decrease in the Atterberg limits (Section 3.1) can be attributed to the substitution of the polar pore water by non-polar hydrocarbons, resulting in a decrease in the ability of the clay particles to form electrochemical bonds and adsorbed layers of water. This is directly confirmed by the EDS results (Section 3.10) where the carbon content is seen to increase and the oxygen content is seen to decrease at the particle surface, and by the FTIR results, which show the presence of new bands of aliphatic and aromatic hydrocarbons, which were not present in the natural soil sample. These results agree with other studies [16,17,18,19,20]. The decrease in MDD and OMC (Section 3.2) is consistent with that of [16,17,21,22] as the specific gravity of the diesel fuel is low. This mechanism is supported by direct observation from SEM (Table 13) where the progressive coverage of the hydrocarbon film and increase in porosity as the contamination level increases is visible. The marked reduction in cohesion with only minor change in friction angle (Section 3.3) is consistent with other literature [17,18,21,22] which indicates that the particles-to-particles cohesive forces are being disrupted, but that the frictional forces are only slightly affected by the presence of contamination. This is corroborated by the XRD results (Section 3.10) which indicate that the peak intensity of the clay minerals is measurably reduced during hydrocarbon intrusion, but the

intensity of quartz is actually near unchanged, and this is why the frictional (sand-dominated) component of strength is largely preserved. The conversion from brittle to ductile behavior (quantified in the Table of stress-strain data and in the softening ratios given in Sections 3.4–3.5) is similar to that reported in [19,23] and is due to the loss of stiffness and to the more gradual release of the stresses after the peak. The rise in compression index and in settlement (Sections 3.6–3.7) is consistent with [16,21] and is directly related to the measured 74% decrease in permeability (Section 3.8) which would result in slower fluid expulsion from pores during settlement and extend settlement time (consistent with [20,23]). The statistical analysis (Section 3.9) also reveals that the greater the contamination, the greater the scatter in soil behavior; a practically important conclusion that suggests that in contaminated zones the parameters should be treated with greater uncertainty than in uncontaminated zones when considering geotechnical design. Overall, the physicochemical interaction between hydrocarbons and soil particles (based on consistent evidence on macro-mechanical, permeability, statistical and microstructural/mineralogical scales) results in a coordinated ensemble of effects including decreases in plasticity and strength, increases in compressibility and settlement, and decreases in permeability. The findings are consistent with the general findings in the literature for contaminated soil mechanics [19,24,25] and demonstrates the need for consideration of contamination effects when designing contaminated ground, and for ground improvement or remediation prior to development of contaminated sites.

7. Conclusion

The present study provided a multi-scale experimental investigation of the impact of diesel fuel contamination on the geotechnical behavior of sandy clay soil (CL) for four contamination levels (0, 2, 5 and 10% by dry weight) using index, compaction, shear strength, stress-strain, softening, compressibility, time-settlement, permeability, statistical, and microstructural (SEM, EDS, FTIR, XRD) tests. The findings support the hypothesis that petrochemical contamination elicits a consistent and coherent array of response from all scales studied. The liquid limit, plastic limit, and plasticity index showed a gradual decrease with contamination and at the index level, the hydrocarbons appeared to replace the pore water in the soil, causing a reduction in plasticity and water affinity. The compaction test demonstrated similar decreases in Maximum Dry Density and Optimum Moisture Content, which are associated with poor packing of particles as a result of the lubricating and low-density properties of the diesel fuel. Shear strength testing showed that the contamination has a significant effect on the reduction of cohesion, from 32 kPa in natural soil to 18 kPa at 10% contamination; the effect on the friction angle was negligible indicating that the primary impact of the contamination is to reduce inter-particle bonding. The fully tabulated stress-strain data showed a clear, quantitative shift from brittle to ductile failure, with an increase in the strain at failure from 3.5% to 7.0%, and the softening ratio from 54.1% to 31.4% from the natural sample to the most contaminated sample. Compression index increased with increase in contamination level from 0.21 to 0.33, which confirmed the trend of increasing compressibility with increasing contamination, as seen in the time-settlement data, which indicated an increase in final settlement by 87.5% at the highest contamination level. As a result of permeability testing, it was found that this behavior is related to a coefficient of permeability decrease of 74% during the consolidation process, thus indicating that the pore spaces are progressively closed when the hydrocarbon coating is applied, thus reducing the permeability. The statistical analysis of replicate testing was conducted and the coefficient of variance for key strength parameters almost tripled from the natural to the most contaminated soil, suggesting that not only is the mean degradation of soil properties due to contamination, the variance is also increased, having direct implications for the reliability-based geotechnical design. Most significantly, for all of the above trends, the SEM imaging showed progressive hydrocarbon film coverage of soil particles, EDS showed a significant increase in surface carbon content, FTIR showed the presence of characteristic absorption bands of aliphatic and aromatic hydrocarbons, and XRD showed the visibility of a measurable decrease in the peak intensities of montmorillonite and illite, with quartz remaining largely unaffected. Finally, regression analysis revealed clear and statistically sound relationships ($R^2 = 0.94 - 0.99$) of contamination level with all measured parameters, making these parameters useful practical predictors for engineering assessments.

Together, the results of this study demonstrate that contamination by the petrochemicals reduce the physical, chemical, mechanical and hydraulic properties of soil in an interrelated manner and that a comprehensive site assessment, soil intervention and designing for contamination are necessary prior to construction on contaminated sites.

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