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Effects of Motor Oil Contamination on the Geotechnical Properties of Clayey Soil (Case Study: Peshawar, Pakistan)

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Abstract: This study investigates the influence of used motor oil contamination on the geotechnical behavior of soils collected from motor-mechanic workshop areas along Kohat Road and Barra Road in Peshawar, Pakistan. Soil samples were obtained from the ground surface and from a depth of 1 m to assess site-specific and depth-dependent variations in soil behavior. Laboratory tests were conducted to evaluate particle-size distribution, Atterberg limits, moisture-related behavior, unconfined compressive strength, and direct shear strength in comparison with uncontaminated control soils. The results show that oil contamination altered the consistency characteristics of the tested soils, with noticeable changes in liquid limit, plastic limit, plasticity index, and flow behavior. These variations indicate that the influence of contamination depends on soil composition, sampling depth, and local site conditions. The mechanical test results further reveal that oil contamination reduced compressive strength and shear resistance, mainly due to the coating and lubricating effect of oil on soil particles, which weakens interparticle bonding, reduces cohesion, and disturbs the soil structure. The reduction in strength was more evident in some surface samples, although the magnitude of degradation varied between the two sites. Overall, the study demonstrates that used motor-oil contamination can significantly affect the engineering performance of soils and should be carefully considered in geotechnical investigation, foundation design, and construction planning in contaminated urban workshop areas.

Keywords: Oil Contamination; Atterberg's Limits; Shear Strength; Soil Classification; Geotechnical Engineering

1. Introduction

The oil contamination of soil is a major environmental and geotechnical concern [1–5], particularly in areas affected by petroleum handling, leakage from storage systems, waste-oil disposal, and motor-mechanic activities [6]. When oil enters the soil, it can alter the interaction between soil particles and pore fluid, thereby changing important engineering properties such as consistency, shear resistance, compressive behavior, and overall load-bearing performance [1–4,7,8]. These changes are significant in geotechnical engineering because contaminated soils may be reused for foundations, road subgrades, and other civil infrastructure without adequate evaluation [3,6].

Fine-grained and clay-bearing soils are particularly sensitive to contamination because their behavior is strongly influenced by surface activity, water interaction, and interparticle bonding [2,3,9]. Previous studies have shown that oil contamination can modify the Atterberg limits and strength parameters of soils, although the reported trends are not always consistent [2,4,8–11]. Some researchers observed increases in liquid limit or plasticity under contamination, while others reported reductions depending on the type of oil, soil characteristics, and testing conditions [2,4,9,11,12]. This inconsistency shows that the response of contaminated soils cannot be generalized and must be interpreted according to the specific material and field conditions [3,6,13].

A reduction in soil strength is one of the most critical engineering effects of contamination. Several studies have reported that contaminated soils exhibit lower unconfined compressive strength, reduced cohesion, and weaker shear resistance, indicating a deterioration in load-carrying capacity [8,10,11,14–16]. Khamehchiyan et al. [10] showed that crude-oil contamination significantly altered the geotechnical properties of both clayey and sandy soils, while Salimnezhad et al. [17] reported similar effects in highly plastic clayey soil under oil contamination and bioremediation conditions. Likewise, Al-Adly et al. [18] found that contamination reduced the bearing performance of sandy soil beneath shallow foundations. These studies confirm that petroleum pollution can have direct implications for geotechnical design and foundation safety [10,14,17,18].

More recent studies continue to show that contaminant type plays an important role in controlling soil response. Karkush and Jihad [13] demonstrated that different oil types produced different changes in the geotechnical properties of clay soil, while Mekkiyah et al. [7] reviewed the effects of crude oil on different soils and summarized available remediation approaches. In addition, Sadiq et al. [19] and Mohammed et al. [20] reported that chemical contamination can significantly affect the engineering behavior of clay-based soils and liner materials. Although these latter studies involve contaminants other than oil, they reinforce the broader conclusion that contamination can substantially modify soil behavior and that such effects must be evaluated experimentally rather than assumed.

Despite the progress made in this field, important gaps remain. Many published studies focus on a single soil type, a single contaminant, or controlled laboratory materials, while fewer investigations compare contaminated soils from real field locations using a combined assessment of consistency and strength properties [6,7,10,16,17]. Site-specific information is especially limited for soils affected by waste oil in urban workshop environments. This is important because soils from different locations may respond differently depending on grading, fines content, plasticity, and local contamination conditions [3,6,13].

Therefore, this study investigates the effect of used motor oil contamination on the geotechnical behavior of soils collected from motor-mechanic workshop areas along Kohat Road and Barra Road, Peshawar, Pakistan. The investigation focuses on the evaluation of Atterberg limits, unconfined compressive strength, and direct shear behavior in order to assess how contamination influences soil consistency and strength. By comparing soils collected from two locations and two depths, the study aims to provide site-specific insight into the engineering behavior of oil-contaminated soils and to contribute useful information for geotechnical assessment in contaminated areas.

2. Methodology

The research employs a detailed experimental methodology to investigate the effect of oil contamination on the geotechnical properties of clayey soil while following established geotechnical testing standards. Soil samples were collected from two sites in Peshawar, Pakistan (Kohat Road and Barra Road Motor Mechanic Workshops), representing a wide range of pollution levels and soil heterogeneity. The geographic coordinates (WGS84) of the sampling sites were recorded as: Kohat Road (°N, °E) and Barra Road (°N, °E). The sample preparation process involved drying the soil at 105 to 110 °C for 24 h to minimise excess moisture, followed by grinding and screening to remove larger particles before contamination control [8,10].

An uncontaminated control soil (0% oil) was prepared and characterized before contamination to establish baseline properties for comparison. The physical/index properties of the control soil (e.g., particle-size distribution/USCS classification, natural moisture content, specific gravity, LL/PL/PI, and baseline strength parameters where applicable) are summarized.

Soil samples were collected from Barra Road and Kohat Road at the surface and at a depth of 1 m. The collected samples were air-dried, sieved, and prepared for laboratory testing in accordance with the relevant ASTM (American Society for Testing and Materials) procedures. The present study focuses on the geotechnical behavior of the tested soils, including particle-size distribution, Atterberg limits, moisture content, compaction-related behavior, unconfined compression, and direct shear characteristics. Used motor oil (SAE 40 grade) was considered as the contaminant in the experimental program; however, detailed physical and chemical characterization of the oil and the site soils was not within the scope of this study. Therefore, the manuscript was revised to report only the results that were directly tested and analyzed, including sieve analysis [11,12], to evaluate particle size distribution and classify soil texture, as previously explored by ASTM International [21]. Sieve analysis was conducted on the four disturbed bulk soils (one per site and depth), producing four gradation curves. Atterberg limits experiments, as described by Devatha et al. [5], were utilised to analyse changes in plasticity index (PI), liquid limit (LL), and plastic limit (PL) in response to oil contamination, as oil disrupts interparticle bonding and alters soil cohesion, as demonstrated by Polyak et al. [22]. Specific gravity [23] was used to analyse density fluctuations, whilst moisture content [24] tests were used to assess water retention capacity and probable hydrocarbon interference in pore spaces, as investigated by ASTM International [25].

To examine the mechanical behavior of contaminated soil, unconfined compression strength (UCS) tests according to Rajabi and Sharifipour [6] were conducted to assess the reduction in strength and deformation characteristics, revealing how hydrocarbons alter soil stiffness and cohesion [26,27]. Furthermore, direct shear experiments [28] were carried out to investigate the effect of hydrocarbon presence on shear strength, internal friction angle, and soil structure stability [29,30].

By comparing contaminated and uncontaminated samples, the investigation determines the degree of strength decrease and compaction variation alterations, emphasising the relationship between oil content and geotechnical behaviour [17,31]. The findings help to better understand the feasibility of contaminated soil for construction applications, as well as potential remediation options such as bioremediation, chemical stabilisation, and soil aeration [32,33].

2.1. Sample Collection

Soil samples were collected systematically to assess the representativeness of oil pollution effects on clayey soil. Soil samples were collected from two unique locations in Peshawar, Pakistan: Kohat Road and Barra Road, as seen in **Figure 1**. Motor Mechanic Workshops were chosen due to their prolonged contact with petroleum products and potential hydrocarbon contamination. These areas are known for frequent oil leaks from vehicle maintenance activities, causing persistent soil degradation and changes in geotechnical features [5,22].

Figure 1. Satellite image of both sites on the Bara and Kohat road.

To reduce external interference, soil sampling was carried out at two different depths: surface soil (0 to 0.5 m) and subsurface soil (0.5 to 1.0 m). This choice was made based on previous research demonstrating that oil contamination largely affects the surface soil layers due to limited hydrocarbon penetration into deeper strata [8,32]. To retain the natural soil structure and contamination distribution, undisturbed samples were retrieved using thin-walled steel tubes, while disturbed samples were gathered using hand augers and bulk sampling procedures. In total, eight (8) field samples were collected across both sites and depths: four (4) disturbed bulk samples (2 sites × 2 depths) and four (4) undisturbed tube samples (2 sites × 2 depths). The four disturbed samples were used for particle-size distribution (sieve analysis) and for preparing the control (0%) and contaminated (3–15%) mixtures as reported by Ayininuola and Bajomo [26]. Each sample was immediately sealed in airtight plastic containers to avoid moisture loss, oxidation, and subsequent contamination, resulting in reliable laboratory testing conditions [34].

In advance of laboratory characterization, preliminary field tests, including odour detection, visual assessment for discoloration, and soil texture analysis, were performed to confirm contamination levels. Contaminated and uncontaminated control samples were clearly marked and stored in regulated conditions to avoid cross-contamination, as identified by Karkush et al. [27]. Site history (workshop type, visible contamination indicators, and sampling date), as well as GPS coordinates, were recorded to ensure traceability and reproducibility. This systematic sampling strategy enables an accurate assessment of geotechnical behaviour changes caused by oil contamination, as well as a comparative examination of impacted and unaffected soil specimens [17,33].

2.2. Sample Preparation

To ensure uniformity, precision, and reliability in testing, the collected soil samples were prepared in accordance with ASTM recommendations and best practices in geotechnical investigations [5, 12]. The preparation process included drying, sifting, contaminant control, and storage to ensure sample integrity for laboratory examination. The first stage in sample preparation was drying the soil to remove excess moisture. Disturbed and undisturbed samples were placed in a controlled-temperature oven at 105 to 110 °C for 24 h, as recommended by Ayininuola and Bajomo [26], to obtain consistent weight and eliminate any residual water content [21, 22]. The stage was followed by Karkush and Resol [8], which was very important because moisture impacts the interaction with hydrocarbons and clay minerals, altering soil plasticity and shear strength.

Following drying, the samples were mechanically disaggregated (**Figure 2**) and sieved to separate coarse and small particles with a sieve shaker [5]. Soil passing through a 2 mm filter was saved for Atterberg limits [12], specific gravity [35], and compaction experiments, whereas coarser fractions were kept for grain size distribution and direct shear testing [28,29,34].

Figure 2. Weighing of the oil-contaminated soil sample.

The substance was intentionally added to samples used in contamination control trials to simulate real-world contamination levels seen at the Kohat Road and Barra Road Motor Mechanic Workshops. This was accomplished by adding calibrated amounts of motor oil and diesel to clean, sieved soil, following the procedures outlined in the studies of Salimnezhad et al. [17] and Ayininuola and Bajomo [26]. To facilitate hydrocarbon absorption and interaction, the contaminated samples were well mixed and left to equilibrate in sealed containers for 48 h [27].

To avoid further contamination or loss of hydrocarbons, all processed samples were stored in airtight plastic containers labelled with GPS coordinates, contamination levels, and depth information [33]. The prepared soil was then used for further laboratory tests, ensuring that both contaminated and uncontaminated control samples were available for comparison.

3. Results and Discussion

3.1. Sieve Analysis of Particle Size Distribution

Soil samples from Barra road, **Figure 3a**, and Kohat road, **Figure 3b**, were examined by sieve analysis, shown in **Figure 3**, at two disparate depths, surface level/1 m down. On both curves, the percentage passing through is evidence of modified soil formation and substance. In nature, one sees a feature common to both locations: the curves for surface samples (red) ought to manifest soft and fine granules rather than coarse ones. Again, this is where the wind has encouraged comparative degradation of the soil over a long period and, nowadays, particle accumulation resulting from fine soil exposure to an atmosphere filled with all kinds of inhumane hands.

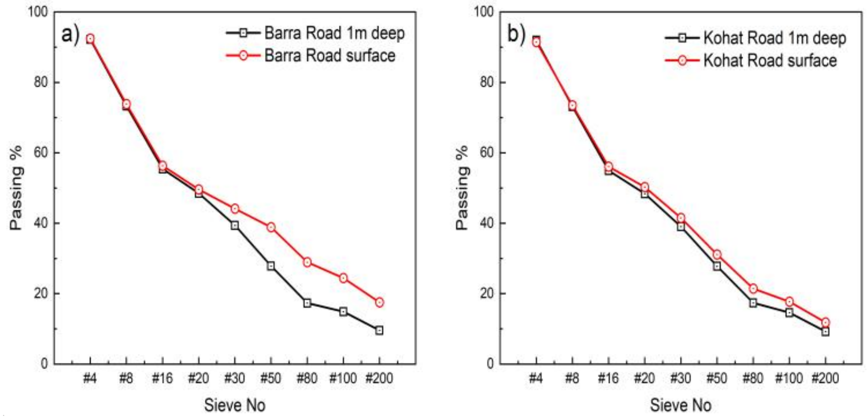

Figure 3. Particle size distribution of soil sample for (**a**) Barra Road, (**b**) Kohat Road.

In contrast, only a small proportion of the 1 m depth samples (black curves) passed through the smaller sieves, indicating that the subsurface soil consists of relatively coarser material. From this phenomenon, we can draw a rather concise conclusion: the sub-surface structures of the soil are relatively stable in almost every case with less clay and silt content.

The Kohat Road samples show relatively consistent soil characteristics between the surface and the 1 m depth, indicating limited variation with depth. In contrast, the Barra Road samples show greater variation between the surface and deeper layers, suggesting a more heterogeneous soil profile and a higher sensitivity to environmental or contamination-related effects. In both locations, the particle-size distribution indicates limited fines content in the upper sieve ranges, which suggests that the soils are predominantly sandy and may not provide the stability typically associated with well-graded materials during compaction.

Figure 4 presents the particle-size distribution results for soil samples collected from Barra Road and Kohat Road at the surface and at 1 m depth. In all cases, sand is the dominant fraction, showing the highest percentage compared with gravel and fines. The gravel fraction is relatively low, while the fine fraction shows only slight variation between the two locations and depths. Overall, the gradation trends for Barra Road and Kohat Road are broadly similar, although minor differences can be observed in the relative proportions of sand, gravel, and fines. To support the classification of the soils as clayey soils, the numerical percentages of gravel, sand, and fine particles for both locations and both depths should be presented and compared with the Atterberg limits.

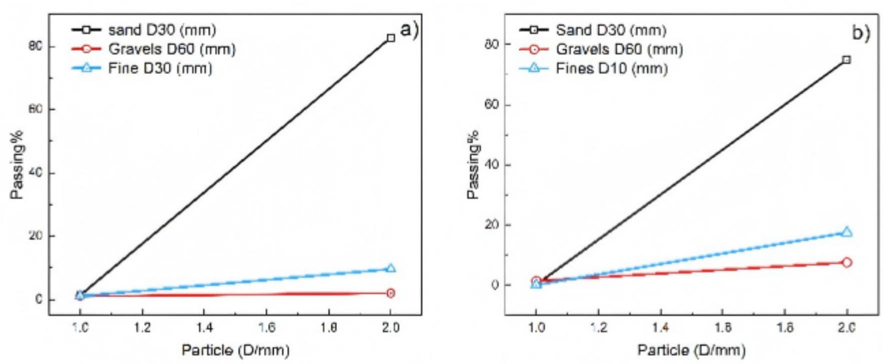

Figure 4. *Cont.*

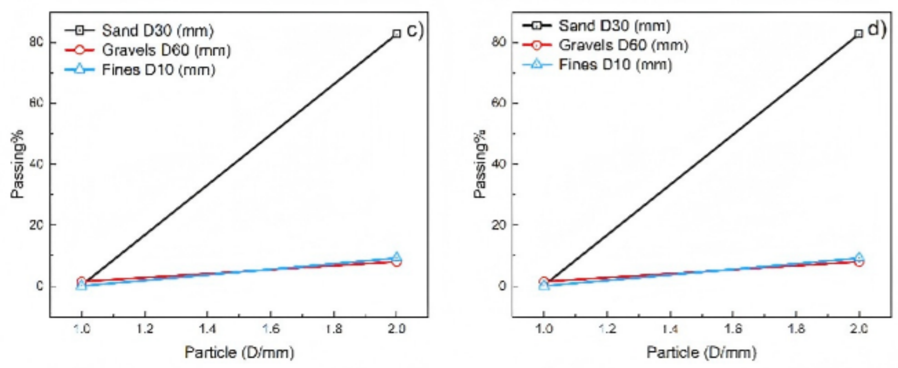

Figure 4. Sieve analysis results: determination of characteristic particle diameters (**a**) Barra Road surface, (**b**) Barra Road deep, (**c**) Kohat Road surface, and (**d**) Kohat Road deep.

3.2. Atterberg's Limits

To clarify and classify these soils, we use Atterberg limits to express how the consistency of fine-grained soils changes with water. The result in **Figures 5 and 6** demonstrates that as the oil content increases. It remains stable compared to the dry state, while soil PL rises and soil PI decreases. The Kohat Road sample was more heavily contaminated than the sample from Barra Road, the result shows. The Atterberg limits of the soil were eroded due to the pollution of oil.

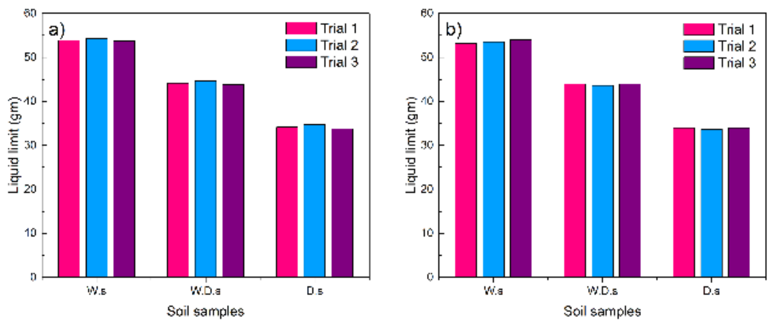

Figure 5. Liquid limit of the (**a**) Kohat Road surface; (**b**) Kohat Road 1 m deep.

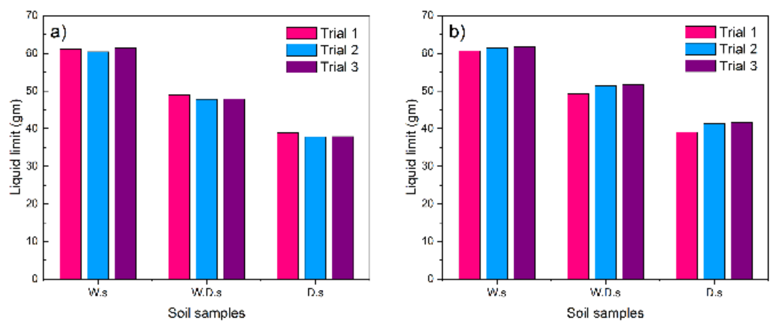

Figure 6. Liquid limit of the (**a**) Barra Road surface; (**b**) Barra Road 1 m deep.

3.2.1. Liquid Limit

Clayey soils are important geomaterials in civil engineering because of their low and great flexibility; yet their vulnerability to hydrocarbon contamination poses significant geotechnical risks. The liquid limit (LL), a major Atterberg limit, provides essential insights into soil behaviour under varying moisture conditions, with standardised testing methods such as the Casagrande cup (ASTM D4318) and fall cone penetrometer (BS 1377) aiding reliable measurement [36–38]. Hydrocarbon contamination changes clay-water interactions through hydrophobic surface coatings and ionic exchange mechanisms, which directly affect the liquid limit values that regulate soil classification (Unified Soil Classification System) and engineering design parameters [33,36,37,39].

The current study (**Figure 7**) demonstrates contradictory liquid limit responses to oil contamination: Crude oil exposure (3–15% by weight) increases kaolinite's liquid limit by 18–27% through particle lubrication effects [37]. Motor oil contamination reduces liquid limits by 15–22% in smectic clays via hydrophobic particle coatings [40]. Diesel fuel introduces intermediate changes (8–12% LL increase) depending on clay mineralogy [16]. The moisture content of the soil that causes it to transition from plastic to liquid is known as the liquid limit, and it is expressed as a percentage of the weight of over-dried soil.

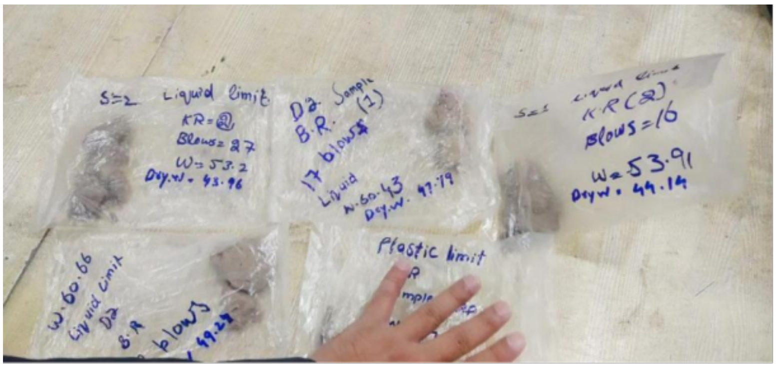

Figure 7. Representative samples of the liquid limit.

Figures 5 and **6** contrast the liquid limit readings of soil samples from two sites, Kohat Road and Barra Road, at both the surface level and a depth of 1 meter, spanning three trials. In both figures, the weight of the container plus wet soil (W.S.) showed the highest values across all trials, followed by the weight of the container plus dry soil (W.D.S.). The lowest values were recorded for the weight of the container (W.C.) and the weight of water (W.W.).

Between the two locations, Barra Road (**Figure 6**) generally showed higher liquid limits across all sample types than Kohat Road (**Figure 5**), suggesting greater moisture retention or clay content. At a depth of 1 m (**Figure 5b**), both sites showed a lower percentage of particles passing the No. 200 sieve compared to the surface samples, indicating a relatively coarser soil composition at depth. In contrast, the surface samples contained a greater proportion of fines. The consistent trend observed across the curves suggests that the measurements were reliable.

The liquid limit (LL) test results for the soil samples from Kohat Road and Barra Road are presented in **Figure 8**. The plots show the relationship between water content and the number of blows for surface and 1 m depth samples tested using the Casagrande apparatus. In both locations, the surface samples exhibited slightly higher liquid limit values than the corresponding deep samples, indicating greater plasticity and a higher water demand to reach the liquid state. This behavior suggests that the surface soils are more responsive to moisture changes than the deeper soils.

At Kohat Road, the decrease in liquid limit from surface to depth was small, indicating relatively consistent consistency behavior with depth. At Barra Road, the reduction was more pronounced, showing a greater variation in plasticity between the surface and deeper layers. These results indicate that the two sites do not respond identically and that soil behavior varies with depth and location. Overall, the liquid limit data are important for understanding the consistency behavior of the tested soils and for assessing their suitability in geotechnical applications under contaminated conditions.

Figure 8 illustrates the liquid limit test results for Kohat Road and Barra Road: (a) Kohat Road surface, (b) Kohat Road deep, (c) Barra Road surface, and (d) Barra Road deep. In all cases, water content decreased with increasing number of blows, as expected from the Casagrande liquid limit procedure. The surface samples from both sites generally showed higher water content values than the deep samples, reflecting slightly higher liquid limit values. Kohat Road showed only minor variation between the surface and deep samples, whereas Barra Road showed a clearer reduction in liquid limit at depth. This indicates that the consistency behavior of the soils varies between the two locations and with sampling depth.

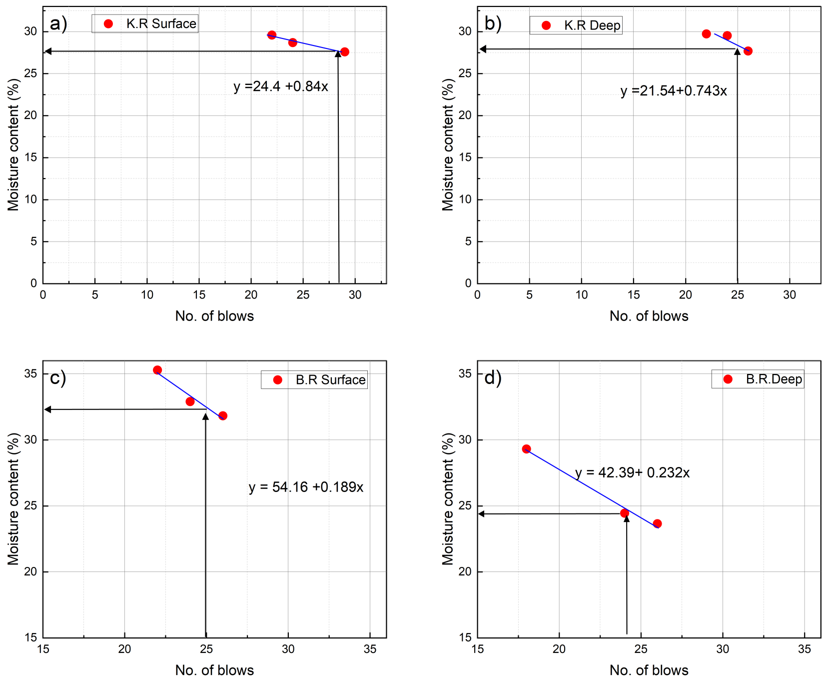

Figure 8. Liquid limit test results for soil samples from Kohat Road and Barra Road: (**a**) Kohat Road surface, (**b**) Kohat Road deep, (**c**) Barra Road surface, and (**d**) Barra Road deep.

3.2.2. Plastic Limit

Soil consistency has significance in geotechnical engineering, especially for comprehending a soil's behavior under different moisture conditions. Two essential indicators utilized to evaluate this behavior are the liquid limit and plastic limit, which delineate the boundaries of the soil's plastic condition. These parameters assist in categorizing soils and assessing their appropriateness for building and various civil engineering applications.

The plastic limit is the moisture content at which soil starts to display plastic characteristics, allowing it to be shaped into threads without disintegrating. The determination is achieved by a series of measurements of the soil's mass in both wet and dry conditions. Higher plastic limits generally indicate higher clay content and increased water retention capacity, which significantly affects the soil's strength and compressibility.

Figure 9 illustrates the plastic limits of soil samples from Kohat and Barra Roads, both at the surface and at a 1-m depth. Kohat Road samples show lower plastic limits, with the surface (≈13.5%) and deep samples (≈14%) closely aligned. In contrast, Barra Road exhibits higher plasticity, with both surface and deep samples showing plastic limit values of about 26%. This indicates greater plastic behavior and moisture sensitivity of the soil; however, no direct conclusion regarding mineral composition or mineralogy can be made from these results alone. The sharp contrast, especially between Kohat deep and Barra deep samples, suggests a considerable difference in soil composition between the two locations, with Barra Road soils being more plastic and potentially more cohesive.

However, **Figure 10a,b** presents a side-by-side comparison of surface and deep soil measurements for two road sites (Kohat Road and Barra Road) across three soil parameters: Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI). The left bar chart shows the absolute percentage values for both surface (blue) and deep (orange) samples, revealing that while Kohat Road exhibits relatively consistent values between depths, Barra Road displays significant discrepancies, particularly in the PI parameter, where surface values are markedly higher than deep values. The right bar chart quantifies these differences as percentage changes from surface to deep, highlighting a dramatic 66.64% decrease in the PI parameter at Barra Road, indicating substantial alterations in soil properties with depth at this location.

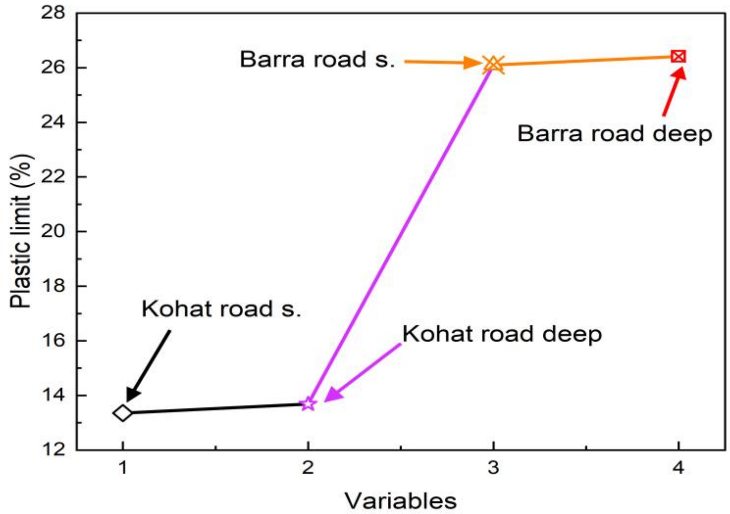

Figure 9. Plastic limits of Kohat and Barra Roads.

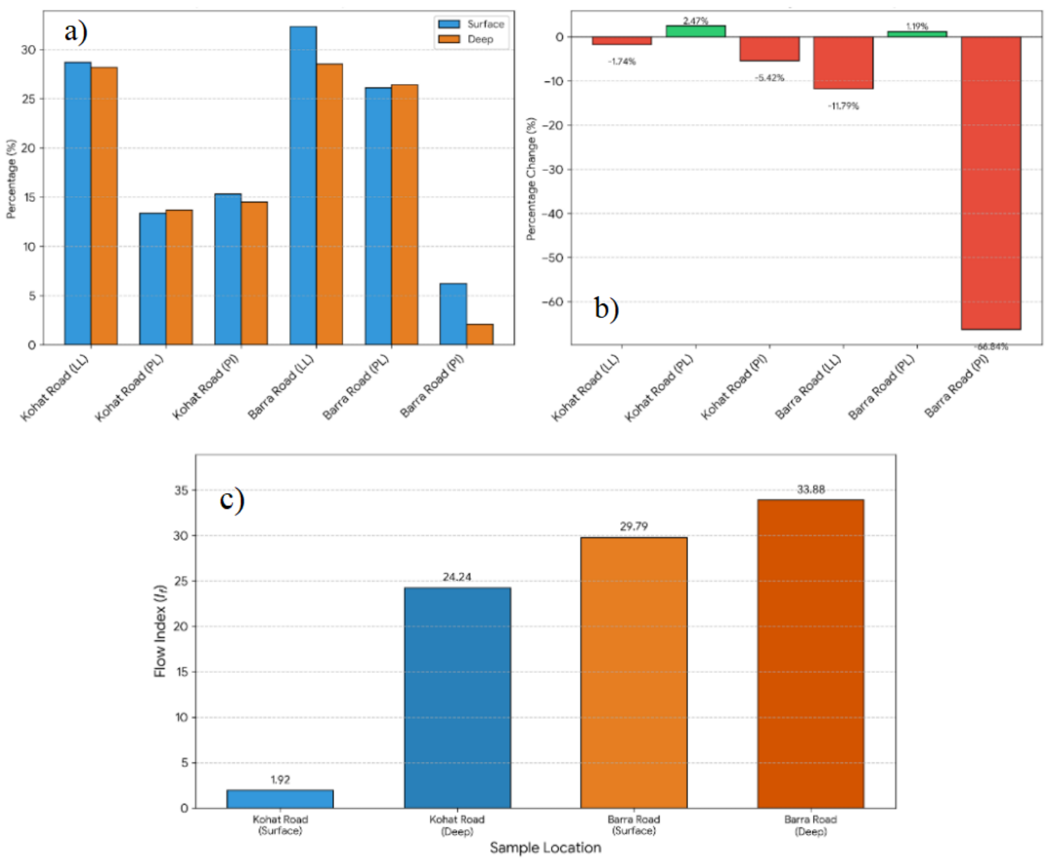

Figure 10. Soil property (**a**) and (**b**) comparison across road sites, (**c**) the flow index.

Figure10c presents a bar chart comparing the soil flow index across four different locations: Kohat Road (Surface) at 1.92, Kohat Road (Deep) at 24.24, Barra Road (Surface) at 29.79, and Barra Road (Deep) at 33.88, indicating a significant increase in the soil flow index with depth and higher values at Barra Road compared to Kohat Road. With increasing oil contamination, the liquid limit and plasticity index generally decreased, indicating a reduction in soil plasticity and water-holding capacity, while the plastic limit showed only minor variation. The flow index also changed with contamination, reflecting a change in the slope of the flow curve and therefore in the sensitivity of the soil consistency to water content.

3.3. Soil Classification

Soil classification was carried out using the Unified Soil Classification System (USCS), in which classification is based on particle-size distribution together with the liquid limit (LL) and plasticity index (PI) obtained from consistency-limit testing [41,42]. Under USCS, soils are classified as coarse-grained when more than 50% of the material is retained on the No. 200 sieve; sand is the fraction passing the No. 4 sieve and retained on the No. 200 sieve, while fines are the fraction passing the No. 200 sieve. The plasticity chart is then used to identify the nature of the fines: points plotting on or above the A-line $PI = 0.73(LL - 20)$indicate clayey fines, whereas points plotting below the A-line indicate silty fines. For coarse-grained soils, samples with 5–12% fines are assigned dual symbols, while soils with more than 12% fines are classified as sands or gravels with fines [43].

Based on the sieve results, all four samples are coarse-grained because the percentage passing the No. 200 sieve ranges from 9.22% to 17.51%, which is far below 50%. The gravel fraction is minor, ranging from 7.55% to 8.54%, while the sand fraction is dominant, ranging from 74.94% to 82.73%. Therefore, the soils at both Barra Road and Kohat Road are sand-dominant rather than purely clayey. Using the reported D10, D30, and D60 values, the gradation criteria for well-graded sand were not satisfied, so the sand fraction is best described as poorly graded. The Atterberg-limit results show that the Kohat Road surface sample (LL = 28.68%, PI = 15.32%) and Kohat Road deep sample (LL = 28.18%, PI = 14.49%) plot above the A-line, indicating clayey fines; accordingly, both are classified as poorly graded sand with clay (SP-SC). In contrast, the Barra Road surface sample (LL = 32.31%, PI = 6.21%) plots below the A-line with about 9.56% fines, so it is classified as poorly graded sand with silt (SP-SM). The Barra Road deep sample contains 17.51% fines and plots below the A-line (LL = 28.50%, PI = 2.09%), so it is classified as silty sand (SM). These results show that the soils are not uniformly clayey; instead, they are predominantly sandy soils with either clayey fines at Kohat Road or silty fines at Barra Road [43].

3.4. Compaction Behavior

The oil reduces the MDD and OMC because of the dissipation of the compaction of hammer energy by oil, which decreases the water absorption. However, **Figure 11a** shows the moisture content components of all soil samples (Barra Road surface and deep, Kohat Road surface and deep). The values for W2 (container + wet soil) and W3 (container + dry soil) are notably higher across all samples, reflecting the presence and loss of water content in W1 values (container weight), and the differences between W2–W3 and W3–W1 support accurate moisture content calculations. Notably, Kohat Road samples, especially the surface, show slightly higher W2 and W3, indicating higher initial water content than Barra Road.

Figure 11b presents a comparative analysis of the total moisture content across the samples. Kohat Road surface soil has the highest moisture content (~32.5%), followed by Kohat Road deep, Barra Road surface, and, lastly, Barra Road deep, which has the lowest moisture content (~29.7%).

Figure 11c presents the moisture content determination for the four soil samples, namely Barra Road surface, Barra Road depth, Kohat Road surface, and Kohat Road depth. In all cases, the values of W2 (container + wet soil) are higher than those of W3 (container + dry soil), while W1 represents the empty container weight. The differences between W2–W3 and W3–W1 were used to calculate the natural moisture content of each sample. The calculated moisture contents were 17.64% for the Barra Road surface, 17.00% for the Barra Road depth, 17.29% for the Kohat Road surface, and 17.50% for the Kohat Road depth. These results show only slight variation among the samples, with the highest value recorded for Kohat Road depth and the lowest for Barra Road depth. Overall, the depth-wise change was small, with a 3.63% decrease at Barra Road and a slight 1.21% increase at Kohat Road.

Oil contamination reduced both the MDD and the OMC of the tested soils. This reduction is attributed to the coating and lubricating effect of oil on soil particles, which decreases interparticle friction, limits water absorption, and reduces the efficiency of compaction energy transfer. Surface soil, particularly at Kohat Road, showed slightly higher moisture retention. In contrast, the lower moisture content at depth, especially at Barra Road, suggests that oil contamination may have restricted water uptake, contributing to the observed decline in compaction performance.

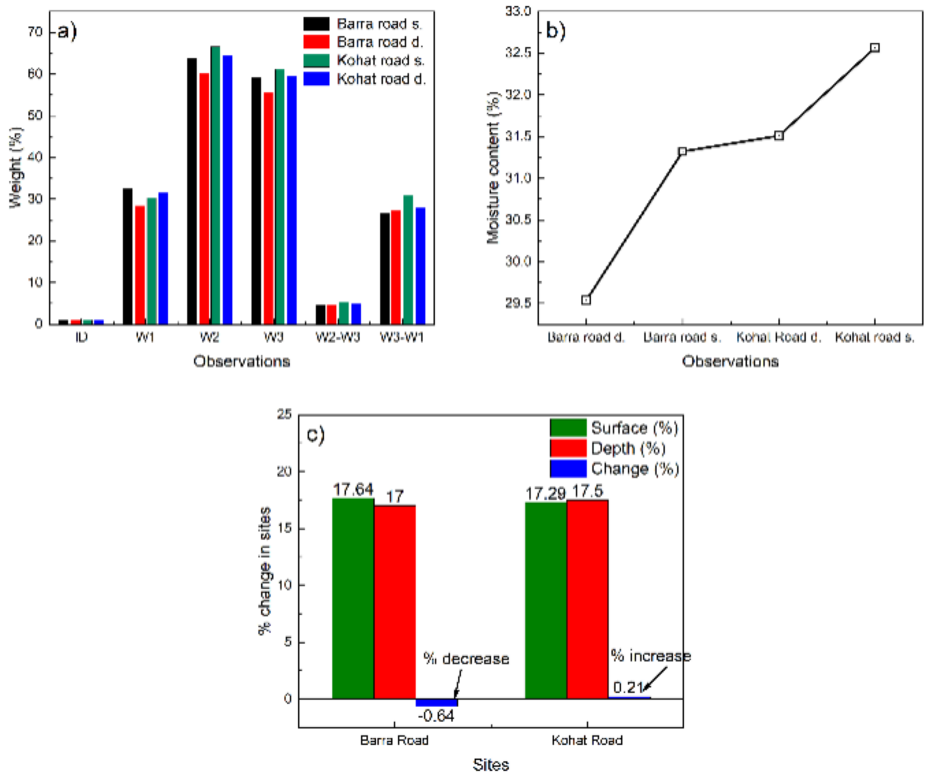

Figure 11. Moisture content of (**a**) all samples; (**b**) evaluation; (**c**) % changes in sites.

3.5. Unconfined Compression Strength Test

The results of this study's unconfined compression strength test revealed a considerable drop in soil strength as oil concentration increased, notably for surface soils from Barra Road. Kermani and Ebadi [15] investigated the effects of oil contamination and subsequent bioremediation on the geotechnical properties of highly plastic clayey soil. Their findings revealed that oil contamination reduces clay-water interactions, increases the plastic limit, decreases the plasticity index by approximately 32%, and lowers shear strength parameters, including cohesion and friction angle, followed by Salimnezhad et al. [17], who first proved how crude oil weakens clayey soils by disrupting particle bonding. More recent investigations support this pattern [8] reported up to 40% UCS reduction in oil-contaminated clays, while Polyak et al. [22] observed that UCS initially increases at very low contamination levels before declining sharply at higher concentrations. The study [14] also confirmed substantial strength losses in sandy clay, emphasizing that the magnitude of reduction is site-specific.

However, our data indicate that oil works as a lubricant in pores, lowering cohesion and stiffness. However, the minor UCS retention in some Kohat Road samples indicates limited contamination, echoing the localised heterogeneity found in recent investigations [14]. Overall, the present study corroborates that oil contamination universally degrades UCS, though the extent depends on soil mineralogy, contamination level, and depth.

The presence of oil within soil pores and among soil particles diminishes cohesiveness. Furthermore, oil lacks the bonding and sticky properties of a pore and inter-particle fluid. Due to its nonpolar nature, oil molecules are incapable of bonding with water or the charged surfaces of clay particles. It will generate an immiscible phase in the soil-water system, functioning as a lubricant, hence reducing the cohesion and unconfined compressive strength of contaminated soil.

Moreover, there is a persistent reduction in failure strain as the oil content increases. The oil contamination first leads to a rapid rise in unconfined compressive strength, followed by a significant decline as the concentration escalates, as shown in **Figure 12**.

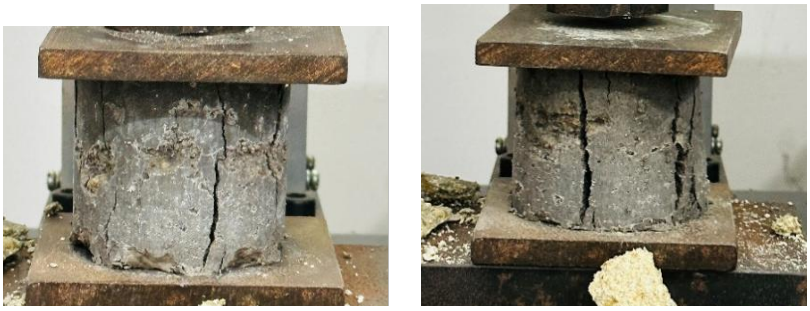

Figure 12. Failure pattern of soil samples of the roads from: (**a**) Barra and (**b**) Kohat.

In **Figure 13a**, the surface sample 01 exhibits a steady increase in stress with load, reaching a peak at 30 kPa, indicating better resistance to deformation. However, **Figure 13b** (sample 02) shows an early peak at around 20 kPa, followed by a flattening curve, suggesting a quicker failure and reduced strength, likely due to higher oil contamination.

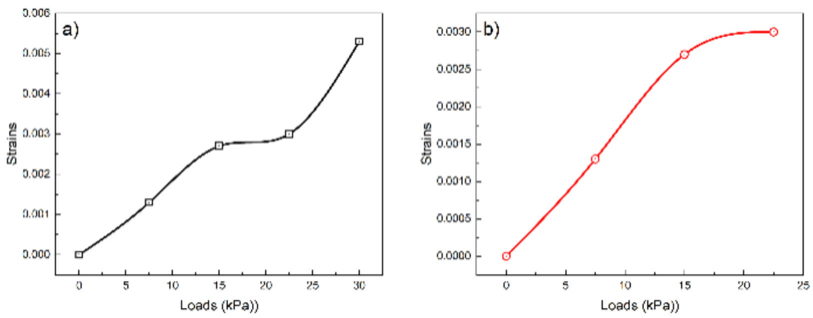

Figure 13. UCS test of Kohat Road surface: (**a**) sample 01; (**b**) sample 02.

Figure 14a,b (deep samples 01 and 02) also demonstrates varying strength behavior. **Figure 14a** displays a more linear and less resistive reaction, whereas **Figure 14b** shows an initially robust response that quickly plateaus, suggesting the negative effects of oil. The presence of oil in soil pores reduces particle cohesion and bonding. Because oil is nonpolar, it cannot bond with water or clay particles, generating a distinct immiscible phase that serves as a lubricant. This lowers cohesion and bonding, hence weakening the structure and reducing UCS. While a modest increase in UCS may occur at very low oil content due to densification effects, higher concentrations result in a significant reduction in UCS and failure strain, indicating the negative influence of oil contamination on soil strength.

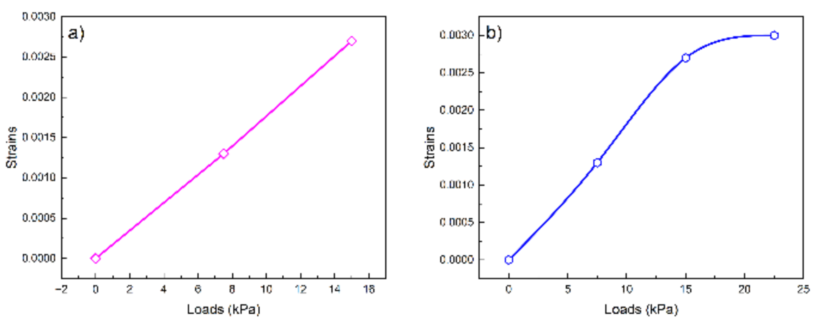

Figure 14. UCS test of Kohat Road 1 m deep: (**a**) sample 01; (**b**) sample 02.

Figure 15 depicts the unconfined compression test results for Barra Road surface samples, with **Figure 15a**

for sample 01 and **Figure 15b** for sample 02. Both samples show a linear and minimum stress-strain response, with a peak stress of around 0.0013 Pa under an 8 kPa load, indicating an extremely low UCS. Compared to the Kohat Road samples (**Figures 13** and **14**), the surface soils of Barra Road display much inferior mechanical characteristics and premature failure, indicating an enhanced vulnerability to deformation under minimum stress.

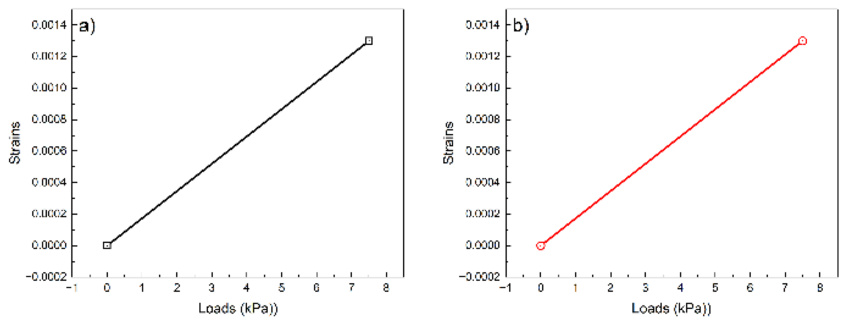

Figure 15. UCS test of Barra Road surface: (**a**) sample 01; (**b**) sample 02.

This low performance can be attributed to oil contamination, which weakens soil by reducing particle cohesiveness. Oil, due to its nonpolar nature and immiscibility with water, displaces pore water and reduces adhesion forces between clay particles, acting as a lubricant. As a result, the soil's structural integrity deteriorates, causing a considerable fall in the UCS. The continuous and mild resistance seen in both samples supports the argument that oil-contaminated surface soils at Barra Road display low load-bearing capacity and reduced stiffness, leaving them unsuitable for supporting structural loads without restoration.

Figure 16 shows the unconfined compression test results for Barra Road's 1m deep soil samples, **Figure 16a** sample 01 and **Figure 16b** sample 02. Sample 01 shows a continuous linear increase in stress-strain behaviour, with a load of 120 kPa and a stress-strain of ~0.023 Pa, indicating high strength and resistance. In comparison, sample 02 (b) peaks at only 16 kPa with stress-strain around 0.0027 Pa, showing a far weaker reaction.

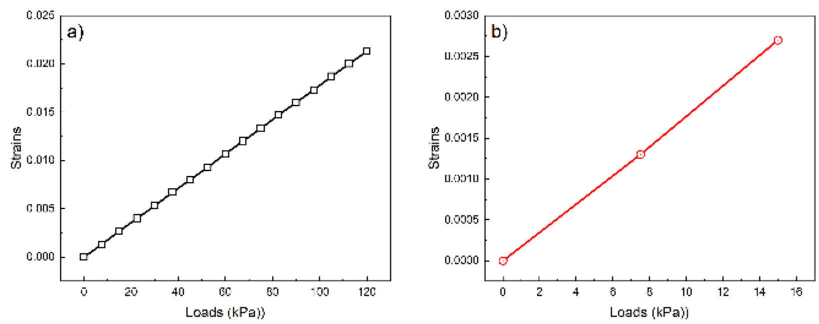

Figure 16. UCS test of Barra Road 1 m deep: (**a**) sample 01; (**b**) sample 02.

Figure 16 shows the unconfined compression test results for Barra Road's 1m deep soil samples, **Figure 16a** sample 01 and **Figure 16b** sample 02. Sample 01 shows a continuous linear increase in stress-strain behaviour, with a load of 120 kPa and a stress-strain of ~0.023 Pa, indicating high strength and resistance. In comparison, sample 02 (b) peaks at only 16 kPa with stress-strain around 0.0027 Pa, showing a far weaker reaction.

The significant variance between these two deep samples highlights potential variations in contamination levels or beneath the soil structure. Sample 01 most likely has low oil influence, keeping greater inter-particle connection and cohesion, resulting in a much higher UCS. In contrast, sample 02 appears to be more influenced by oil, which, as a non-polar and non-adhesive fluid, reduces clay-water interactions and weakens soil strength by forming a lubricating, immiscible phase. These data demonstrate that oil contamination at depth can fluctuate, and its presence normally lowers UCS and soil stiffness, albeit certain situations may maintain some strength in less-impacted locations.

However, in **Figure 17a**, the Kohat Road results show that surface sample 1 developed the highest peak load (30.0) at a strain of 0.0053, whereas deep sample 1 showed the lowest peak load (15.0) at a strain of 0.0027. Surface sample 2 and deep sample 2 both reached an intermediate peak load of 22.5 at a strain of 0.0030. Overall, the Kohat Road surface samples exhibited slightly higher load-carrying capacity than the deep samples, although some variability was observed.

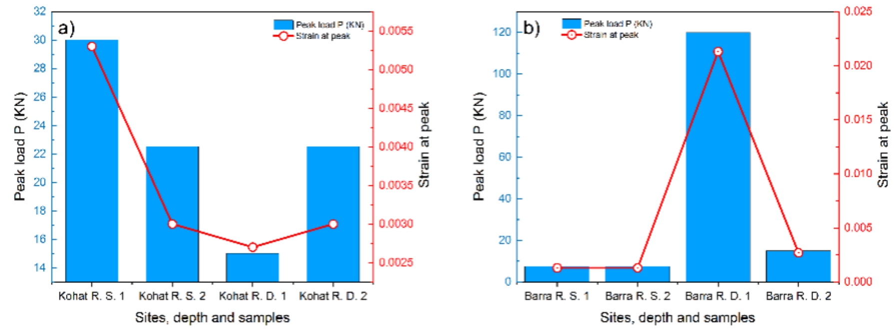

Figure 17. Comparison of peak load and corresponding strain for UCS test samples from (**a**) Kohat Road and (**b**) Barra Road at surface and deep levels.

In **Figure 17b**, the Barra Road results show a marked difference between surface and deep samples. Both surface samples reached only 7.5 at a strain of 0.0013, indicating the weakest response. Deep sample 2 reached 15.0 at a strain of 0.0027, while deep sample 1 developed the highest peak load of 120.0 at a strain of 0.0213. Overall, the deep samples showed greater load-carrying capacity than the surface samples, although the large difference between the two deep samples indicates substantial variability in behavior.

3.6. Direct Shear Test

The direct shear test results in this investigation demonstrated a noticeable decline in shear strength with increasing oil pollution, especially in Kohat Road soils. According to their research, oil contamination lowers shear strength characteristics like cohesiveness and friction angle, raises the plastic limit, decreases the plasticity index by around 32%, and diminishes clay-water interactions [17], who showed that hydrocarbons inhibit inter-particle bonding, resulting in decreased shear resistance. The study also discovered significant decreases in cohesiveness and friction angle in contaminated clays, attributing this effect to pore fluid replacement and lubrication [8].

Recent studies have confirmed these conclusions. The study [22] showed that oil-contaminated clays incur up to 35–45% losses in shear strength, with bioremediation partially restoring strength characteristics. Researchers [14] discovered that sandy clays contaminated with crude oil have much lower cohesiveness and internal friction angle, emphasising the site-specific response of diverse soils.

The current study expands on previous findings by comparing two unique sites: Barra Road soils retained considerably better shear resistance at depth, whereas Kohat Road soils showed a continuous strength decrease. This site-dependent variation supports recent studies [14], which show that contamination effects on shear strength are substantially dependent on mineralogy, contamination depth, and hydrocarbon type.

Quantitative shear tests were conducted to determine the shear strength of the samples. As the oil content in the soil samples increases, the stress-displacement diagram shifts downward, resulting in a drop in soil strength. This test reveals that oil operates similarly to water; it raises the capacity for inter-particle mobility, hence decreasing the shear strength of polluted soils.

Figure 18 depicts the direct shear test results for two soil samples, Barra Road (**Figure 18a**) and Kohat Road (**Figure 18b**), at a depth of one metre. Both plots show a positive linear relationship between normal stress and horizontal (shear) stress, indicating typical shear strength behaviour in cohesive soils. Barra Road (**Figure 18a**) had greater shear resistance, with horizontal stresses of around 190 units under a 200 kPa normal load, showing improved interparticle bonding and frictional resistance, which could be attributed to reduced oil pollution at the testing depth. Kohat Road (**Figure 18b**) has lower horizontal stresses (~172 at 200 kPa), indicating reduced cohesion due to residual oil affecting particle bonding.

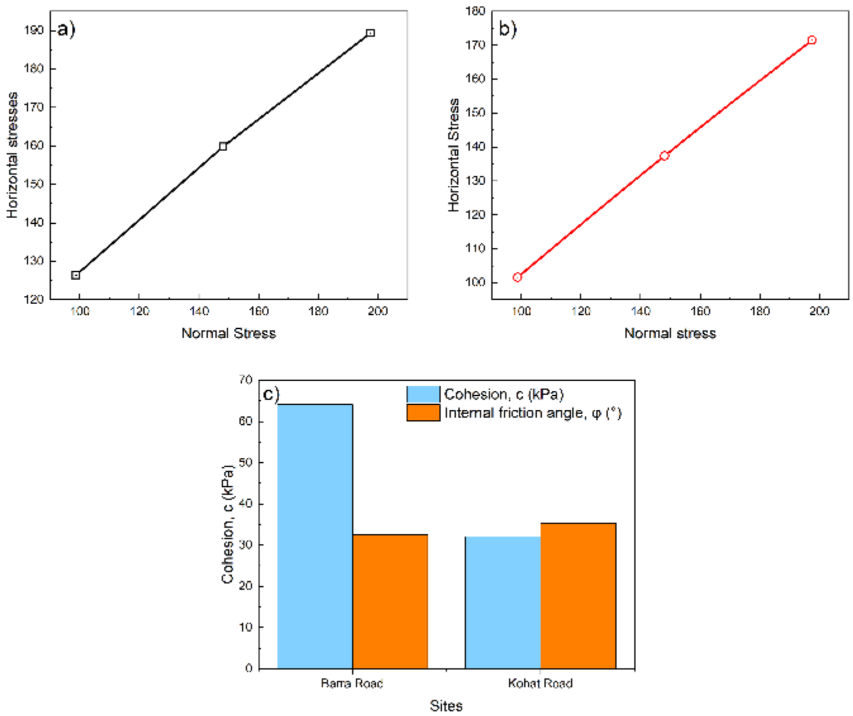

Figure 18. Direct shear test of (**a**) Barra Road, (**b**) Kohat Road 1m deep, and (**c**) comparing cohesion and friction angle.

Figure 18c compares the direct shear strength parameters of the contaminated deep soil samples from Barra Road and Kohat Road. Barra Road deep soil showed higher cohesion (64.11 kPa) than Kohat Road deep soil (32.06 kPa), indicating greater cohesive resistance. In contrast, Kohat Road deep soil exhibited a slightly higher internal friction angle (35.28°) than Barra Road deep soil (32.51°), indicating greater frictional resistance. Overall, the results show that contamination affected the two soils differently: Barra Road remained more cohesion-dominated, whereas Kohat Road exhibited relatively higher frictional behavior. These findings suggest that oil contamination reduces shear strength, but the extent of reduction depends on soil type, depth, and the inherent properties of the soil.

4. Discussion

This study shows that oil contamination altered the geotechnical behavior of the tested soils from Kohat Road and Barra Road, particularly in terms of consistency limits and strength characteristics. The results are generally consistent with previous studies reporting that contamination can modify Atterberg limits and reduce soil strength, although the magnitude and direction of change depend on the nature of the soil and the contaminant [2,4,8,17]. In the present study, the Kohat Road soils generally exhibited higher plasticity and more clay-influenced behavior, whereas the Barra Road soils were more sand-dominant and less plastic. This difference indicates that the effect of contamination is site-dependent and strongly influenced by the initial soil characteristics [13,44].

The Atterberg limit results showed that oil contamination changed the liquid limit, plastic limit, and plasticity index in a non-uniform manner. In some samples, the liquid limit and plasticity index were reduced, whereas in others the variation was less pronounced. These observations confirm that contamination affects soil consistency behavior, but the response cannot be generalized for all soils [2,4]. Similar contaminant-related changes in fine-grained soils have also been reported in other studies. For example, Sadiq et al. [19] reported that chemical contamination significantly influenced the engineering behavior of clayey soil, while Mohammed et al. [20] showed that contamination altered the properties of clay liner materials and affected their geotechnical response. In the present study, the observed variation between Kohat Road and Barra Road further supports the conclusion that the influence of contamination depends on site conditions and soil type [13,44,45].

A second important result of this study is the reduction in soil strength under contaminated conditions. The unconfined compression and direct shear results indicate that oil contamination adversely affected the load-carrying capacity of the tested soils. This agrees with earlier findings showing that contamination can reduce interparticle bonding and weaken the overall soil structure [8,17,46]. In the current study, the contaminated soils from Barra Road and Kohat Road did not behave identically, which again highlights the importance of local soil characteristics. Similar reductions in engineering performance under contamination were also reported by Al-Adly et al. [18], who found that crude-oil contamination decreased the bearing capacity of sandy soil beneath shallow foundations. The present results, therefore, support the view that contamination can significantly reduce soil resistance and must be considered in foundation assessment and design [8,17].

From an engineering application perspective, the results indicate that contaminated soils should not be treated in the same way as uncontaminated ground. Changes in consistency limits and reductions in strength parameters can affect foundation stability, subgrade performance, and the suitability of soil for construction purposes. For this reason, site-specific geotechnical testing is necessary where oil contamination is suspected. Although remediation was not experimentally evaluated in this study, previous research has shown that improvement methods may help restore contaminated soil performance. Nazir et al. [11], for example, reported that magnesium oxide improved the geotechnical-environmental behavior of contaminated clay soil, while Mohammed et al. [20], Sohel et al. [46], and Klamerus-Iwan et al. [47] showed that stabilization can improve contaminated liner soils. Therefore, where significant degradation is identified, treatment or stabilization may be considered as part of the engineering response.

Despite these findings, the present study has several limitations. First, the investigation was based on soils collected from only two locations, so the conclusions should be interpreted as site-specific rather than universally applicable. Second, the study focused only on the experimentally measured properties, namely particle-size distribution, consistency limits, unconfined compressive strength, and direct shear behavior. Mineralogical analysis, chemical characterization of the oil, permeability, compressibility, and micromorphology were not included; therefore, the discussion was limited to the observed geotechnical response of the tested soils. This limitation should be considered when comparing the results with broader contamination studies [3,22,48]. Future work should include controlled contamination levels, mineralogical characterization, and additional testing so that the mechanisms of soil–oil interaction can be evaluated more completely.

5. Conclusions

This study shows that oil contamination affects the geotechnical behavior of the tested soils from Kohat Road and Barra Road. The results indicate changes in consistency limits, unconfined compressive strength, and shear strength, which are important for geotechnical design and foundation performance in contaminated ground. Based on the present investigation, the following conclusions can be drawn:

1. Reduction in soil strength: The tested soils showed a reduction in strength under oil-contaminated conditions, as reflected by decreases in unconfined compressive strength and changes in direct shear parameters. This behavior indicates that oil contamination can weaken soil structure by reducing interparticle resistance.
2. Changes in consistency behavior: The Atterberg limit results showed variations in liquid limit, plastic limit, and plasticity index between the two sites and depths, indicating that oil contamination influences the consistency behavior of the soils. The magnitude of change depended on the characteristics of the soil at each location.
3. Site-specific response: The two sites did not respond in the same way. Kohat Road soils generally showed higher plasticity and more clay-influenced behavior, whereas Barra Road soils were more sand-dominant with lower plasticity. This indicates that the effect of oil contamination depends strongly on the initial soil characteristics.
4. Engineering significance: The observed changes in strength and consistency indicate that oil-contaminated soils may require careful evaluation before use in engineering works. For this reason, site-specific laboratory testing should be considered when assessing contaminated ground for foundation and construction purposes.

These findings emphasize the importance of accounting for oil contamination in the geotechnical evaluation of soils intended for construction in affected areas. The observed changes in consistency and strength indicate that contaminated soils may show reduced engineering performance and, therefore, require careful site-specific assessment before foundation or infrastructure development. Accordingly, laboratory testing of contaminated soils should be considered an essential step in evaluating their suitability for engineering use. Future research should expand the available data by examining a wider range of contamination conditions and soil types to improve understanding of contaminated-soil behavior under practical field conditions.

Author Contributions

Conceptualization, S.R. and A.S.; methodology, S.R.; software, S.R.; validation, S.R., A.S., and N.I.; formal analysis, S.R.; investigation, A.S.; resources, T.I.J.; data curation, S.R.; writing—original draft preparation, S.R.; writing—review and editing, T.I.J.; visualization, S.R.; supervision, N.I.; project administration, A.S.; funding acquisition, A.S.I. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable. This study does not involve human participants, animals, or any ethical considerations.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors used ChatGPT to improve language consistency, readability, and grammatical clarity. QuillBot and Grammarly were used for limited paraphrasing support. All scientific content, data interpretation, results, conclusions, and final revisions were reviewed and verified by the authors, who take full responsibility for the accuracy and integrity of the manuscript.

Abbreviations

Abbreviation	Full Name
ASTM	American Society for Testing and Materials
USCS	Unified Soil Classification System
LL	Liquid Limit
PL	Plastic Limit
PI	Plasticity Index

UCS	Unconfined Compressive Strength
Gs	Specific Gravity of Soil Solids
OMC	Optimum Moisture Content
MDD	Maximum Dry Density
MC	Moisture Content
D10	Effective particle size corresponding to 10% passing (mm)
D30	Particle size corresponding to 30% passing (mm)
D60	Particle size corresponding to 60% passing (mm)
W	Water content (%)
W1	Weight of empty container
W2	Weight of container + wet soil
W3	Weight of container + dry soil
W.C.	Weight of the container
W.W.	Weight of water
W.D.S.	Weight of dry soil
KR	Kohat Road
BR	Barra Road
S	Surface sample
D	Deep sample
c	Cohesion (kPa)
φ	Internal Friction Angle (°)

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