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Influence of Lead Contamination on Soil Index Properties: Implications for Geotechnical Engineering

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Abstract

Environmental pollution, particularly heavy-metal contamination, poses increasing challenges for geotechnical engineering as soils in urban and industrial regions become progressively altered by toxic ions. Despite growing concern, limited empirical data exist on how specific contaminants such as lead (Pb^{2+}) influence fundamental soil index properties that govern classification and foundation performance. This study addresses this gap by experimentally evaluating the effects of varying lead nitrate concentrations (10–30 g) on the Liquid Limit, Plastic Limit, Plasticity Index, Specific Gravity, and Moisture Content of a lateritic soil. Contaminated samples were prepared under controlled laboratory conditions and tested following standard geotechnical procedures. Results show a consistent reduction in Liquid Limit and Plasticity Index with increasing lead concentration, indicating diminished soil liquidity and plasticity due to flocculation and reduced diffuse double-layer thickness. Specific Gravity and Moisture Content increased steadily, reflecting particle densification and enhanced water retention linked to physicochemical interactions between Pb^{2+} ions and the soil matrix. Plastic Limit exhibited minimal change, suggesting limited sensitivity to contamination. These findings provide concentration-dependent insights into how lead alters soil behaviour, offering valuable guidance for geotechnical assessment in pollution-affected environments. The study highlights the importance of integrating contamination analysis into soil classification and foundation design, particularly in industrialised and rapidly urbanising regions.

Keywords: Lead contamination; Soil index properties; Geotechnical behaviour; Environmental, Geotechnics

1. Introduction

Environmental pollution has emerged as one of the most critical challenges confronting rapidly urbanising and industrialising regions, particularly in low- and middle-income countries where weak regulatory frameworks, limited waste management infrastructure, and intensive anthropogenic activities contribute to widespread soil degradation. Among various pollutants, heavy metals occupy a distinct position due to their toxicity, non-biodegradability, and long-term persistence in the environment. Lead (Pb), in particular, is frequently introduced into soils through industrial effluents, battery disposal, paint residues, vehicular emissions, smelting operations, metal workshops, and contaminated stormwater runoff [1]. Once introduced into the soil matrix, lead binds strongly to fine particles and organic matter, altering the physicochemical and microstructural behaviour of soils in ways that can significantly influence their engineering performance.

The geotechnical implications of heavy metal pollution are receiving increased research attention due to growing evidence that contaminated soils often exhibit modified index and engineering properties. Several studies have shown that heavy metals may alter soil fabric, interparticle forces, and mineralogical interactions, leading to measurable changes in critical parameters such as Atterberg limits, specific gravity, moisture retention, compaction behaviour, and shear strength [2, 3]. These alterations can directly influence foundation performance, slope stability, settlement behaviour, and general soil–structure interaction. As developing nations expand their built environments into previously industrialised or polluted zones, understanding the behaviour of contaminated soils becomes essential for safe and sustainable infrastructure development.

Lead contamination is known to affect soil consistency by interacting with clay minerals, influencing diffuse double-layer thickness and modifying water adsorption behaviour. Reported studies indicate that Pb^{2+} ions can either flocculate or disperse clay particles depending on concentration and ionic strength, thereby affecting liquid limit, plastic limit, and plasticity index [4]. Research conducted in the last decade has also highlighted that lead-contaminated soils may show enhanced particle density due to the relatively high atomic weight of lead compounds, which can result in increased specific gravity values [5]. Moreover, lead-induced changes in pore-water chemistry may modify water retention characteristics, influencing moisture content and compaction response [6]. These changes have practical importance because foundation design relies heavily on accurate estimation of soil index parameters, which serve as preliminary indicators of soil behaviour and engineering suitability.

Despite these emerging insights, the literature reveals notable gaps. Many existing studies focus on broad environmental impacts of lead pollution or its ecological consequences, with comparatively fewer investigations addressing its specific influence on soil index properties under controlled laboratory conditions. More so, some available studies consider heavy metal mixtures or complex industrial pollutants, making it difficult to isolate the distinct effects of lead salts on geotechnical properties. Several authors have emphasised the need for more controlled experimental datasets that examine concentration-dependent trends, enabling the development of predictive models and improved geotechnical decision-making frameworks for contaminated sites [7, 8].

The need for such studies is particularly important in regions where informal industrial activities such as metal fabrication, auto-mechanic operations, and battery recycling are prevalent and often unregulated. In such contexts, soils accumulate substantial quantities of heavy metals over time, yet geotechnical assessments conducted during construction planning frequently overlook contamination-induced property changes. This oversight can result in inaccurate classification, misleading foundation recommendations, and potential structural distress in the long term.

In light of these considerations, systematic laboratory evaluation of soil contaminated with varying concentrations of lead salts provides a valuable contribution to the understanding of how pollution alters fundamental index properties. These parameters namely; liquid limit, plastic limit, plasticity index, specific gravity, and moisture content form the basis for soil classification and preliminary engineering assessment. Establishing concentration-dependent relationships offers a clearer scientific basis for interpreting contaminated soils and supports more informed decisions in foundation design, environmental remediation, and pollution management.

2. Review of Literature

Heavy-metal pollution has become a significant concern in environmental geotechnics due to its profound effects on soil microstructure, index behaviour, and engineering performance. Lead (Pb), one of the most prevalent contaminants in urban and peri-urban environments, continues to attract scholarly attention because of its persistence, toxicity, and strong interactions with clay minerals and organic matter. The presence of Pb^{2+} ions in soils induces physicochemical alterations that can modify the engineering properties required for classification, compaction, and foundation design. As urban expansion increasingly encroaches upon contaminated or industrially impacted soils, understanding these interactions has become crucial for safe geotechnical practice.

Lead contamination affects soil behaviour primarily through ion exchange, surface adsorption, and modification of the diffuse double layer of clay particles. The mechanisms and implications of these interactions have been widely discussed, with studies indicating that Pb^{2+} ions adsorb strongly onto negatively charged soil surfaces, replacing native cations such as Ca^{2+}, Mg^{2+}, and Na^{+}, and altering electrochemical stability [9]. These ionic substitutions can influence Atterberg limits and soil consistency. Several experimental studies conducted between 2020 and 2025 have demonstrated that lead salts tend to reduce the liquid and plastic limits in kaolinitic and lateritic soils due to flocculation and reduced repulsive forces between particles [10, 11]. In contrast, soils with high montmorillonite content sometimes exhibit increased plasticity under moderate Pb concentrations, highlighting the role of mineralogy in mediating pollutant effects [12].

Specific gravity, an important index parameter for soil classification, is also sensitive to heavy-metal contamination. Due to its relatively high atomic weight, lead incorporation often results in higher particle densities. Recent work in West Africa found that specific gravity increased consistently with rising Pb concentration in lateritic soils, attributing this trend to the adsorption of heavy ions and precipitation of secondary Pb-bearing minerals [13]. Similar outcomes were reported in East Asian studies, where progressive increases in specific gravity were linked to the formation of metal–clay complexes and densification of particle surfaces [14].

Compaction characteristics also exhibit notable changes under lead pollution. Several authors have suggested that Pb contamination can cause an increase in maximum dry density (MDD) and a reduction in optimum moisture content (OMC), reflecting changes in particle packing and reduced water demand during compaction [15]. However, contrasting observations have been reported in expansive clays, where higher Pb concentrations resulted in increased OMC and decreased MDD due to disrupted layered structures and heightened water adsorption [16]. These divergence patterns underscore the influence of soil type, mineralogy, and ionic chemistry on the compaction process.

Beyond index properties, heavy-metal contamination affects shear strength and compressibility. Laboratory experiments have shown that lead can reduce undrained shear strength by decreasing physico-chemical bonding between clay particles and enhancing structural instability [17]. More recent investigations in South Asia indicated that soil polluted with Pb exhibited lower cohesion (c) and internal friction angle (φ), with researchers attributing these reductions to the collapse of interparticle bonding and microstructural rearrangement [18]. In granular–clay mixtures, however, moderate Pb concentrations were associated with increased apparent cohesion due to short-term cementation effects [19], illustrating the complexity of contamination processes.

Lead pollution also affects water retention and pore-fluid behaviour. Pb-induced changes in soil–water characteristic curves have been documented, with several studies reporting reductions in capillary suction in kaolinitic soils and increases in moisture retention in smectitic soils [20]. These differences reflect how Pb interacts differently with various mineral groups, either reducing or enhancing adsorption mechanisms.

Migration and persistence of heavy metals in subsoils pose additional engineering and environmental concerns. Investigations conducted in 2024 demonstrated that repeated wetting and drying cycles facilitate the downward movement of Pb ions, which gradually modify deeper soil layers and potentially compromise their engineering integrity [21]. Such mobility increases the complexity of foundation assessments in historically polluted sites. Additionally, lead has been shown to reduce hydraulic conductivity in clayey soils due to pore clogging by precipitated Pb compounds [22], while similar reductions have been observed in sandy soils due to blockage of interconnected pores by metal oxides [23].

Although significant progress has been made in understanding heavy-metal-induced changes in soil properties, notable gaps remain. Much of the existing literature relies on mixed-pollutant field soils, which makes it difficult to isolate the specific effects of lead salts. Other studies focus narrowly on a single geotechnical parameter or use only one contamination level, limiting the applicability of their findings. Two recent systematic reviews emphasised the need for controlled, concentration-dependent laboratory studies to establish predictive models and to support better geotechnical decision-making in contaminated terrains [24, 25]. Additionally, researchers have called for studies that incorporate both index and engineering properties into integrated analyses to better understand the implications of Pb contamination for foundation performance [26].

Literatures consistently demonstrates that lead contamination affects soil consistency limits, specific gravity, compaction characteristics, shear strength, permeability, and moisture behaviour. However, variations across soil types and contamination scenarios highlight the necessity for laboratory studies that investigate concentration-dependent relationships under controlled conditions. These insights are essential for improving soil classification, foundation design, environmental remediation, and sustainable construction practices in pollution-impacted environments.

3. Methodology

3.1 Area of Study

Edo State Polytechnic, Usen, located in Ovia South-West Local Government Area of Edo State, Nigeria, serves as a significant academic and technological hub in southern Nigeria. Geographically, the institution is situated approximately between Latitudes **6°32'–6°33' N** and Longitudes **5°17'–5°18' E**, with an average elevation of about **145–150 m above sea level**. The campus occupies a spacious semi-rural environment characterised by lateritic soils, gently undulating terrain, and a mix of educational and residential land uses. Its proximity to Benin–Lagos Highway enhances accessibility and regional connectivity. The Polytechnic's serene setting, relatively low industrial activity, and limited vehicular pressure make it an ideal **control or baseline study area** for environmental and geotechnical assessments. Compared with urbanised and industrial zones in Benin City, the Usen environment offers minimally disturbed soil conditions, enabling researchers to evaluate natural soil behaviour, physicochemical properties, and background heavy-metal concentrations for comparative analysis.

3.2 Soil Sampling and Characterisation

A disturbed soil sample was collected from a site characterised by typical lateritic profiles common to urban construction zones in southern Nigeria. The sampling location lies within an area influenced by light industrial activities and vehicular emissions, ensuring a representative baseline soil for evaluating the effects of controlled contamination. The soil was air-dried, pulverised gently, and passed through a 2 mm sieve to remove large aggregates and debris. Initial characterisation included the determination of natural moisture content, particle size distribution, Atterberg limits, and specific gravity to establish the baseline properties of the uncontaminated soil. These properties provided reference data for comparing contamination-induced variations.

3.3 Particle Size Distribution

Particle size distribution was determined using the hydrometer–sedimentation (Jar) test. The jar test was employed as a complementary screening tool to evaluate the approximate percentages of sand, silt, and clay. A composite soil sample was mixed thoroughly with a dispersing agent in a transparent jar, vigorously shaken, and allowed to settle for 24 hours. Sequential sedimentation layers corresponding to sand, silt, and clay fractions were measured visually and converted to percentage distributions. This approach enabled soil textural classification and guided subsequent interpretation of Atterberg limits. Classification was performed using both the USDA soil texture triangle and the AASHTO system, integrating particle-size results with plasticity characteristics.

3.4 Preparation of Contaminant Solutions

Analytical-grade lead nitrate ($Pb(NO_3)_2$) was used as the contaminant. Five solutions were prepared using distilled water, corresponding to contamination levels of 10 g, 15 g, 20 g, 25 g, and 30 g per 10 kg of soil. Each solution was thoroughly dissolved to ensure homogeneity prior to application. The concentration range was selected to simulate low-to-high contamination intensities comparable to values reported in urban and industrial soils in previous studies.

3.5 Contamination Procedure

Five plastic containers were filled with 10 kg of the prepared soil. Each container received one of the lead solutions and was thoroughly mixed to ensure uniform distribution of the contaminant. Containers were air-sealed and kept undisturbed for 30 days to allow adequate contact time for adsorption, ion exchange, and contaminant–soil interaction. This curing period enabled the contaminated soil to achieve realistic physicochemical equilibrium conditions before laboratory testing commenced.

3.6 Laboratory Tests on Contaminated Soil

3.6.1 Atterberg Limits

Liquid limit (LL), plastic limit (PL), and plasticity index (PI) were determined in accordance with ASTM D4318. For each contamination level, soil samples were air-dried, sieved, and subjected to consistency limit tests. Devices such as the Casagrande apparatus and grooving tools were used following standard procedures. The influence of lead contamination on soil consistency was evaluated by analysing variations in LL, PL, and PI relative to the baseline sample.

3.6.2 Specific Gravity

Specific gravity of the soil solids was determined following ASTM D854. A pycnometer was used, and each contaminated sample was tested separately. Specific gravity values were compared across the contamination gradient to quantify density changes attributable to lead adsorption and mineralogical alteration.

3.6.3 Moisture Content

Moisture content was measured using the oven-drying method (ASTM D2216). Soil samples were weighed, oven-dried at 105°C for 24 hours, cooled, and re-weighed. The moisture content trend across contamination levels provided insights into lead-induced modifications in water retention behaviour.

3.7 Data Analysis

Regression analysis was performed to model the quantitative relationship between contamination concentration and each soil property. Microsoft Excel was used to plot trend lines and compute coefficients of determination (R^2) for linear and potential non-linear relationships. The best-fit models were selected based on statistical performance and consistency with observed soil behaviour. Trends were interpreted with reference to physicochemical mechanisms, mineralogical context, and relevant literature.

4. Results

4.1 Laboratory Test

The table 1 presents the quantitative results obtained from the laboratory evaluation of soil samples artificially contaminated with increasing concentrations of lead nitrate. Five concentrations—10 g, 15 g, 20 g, 25 g, and 30 g—were introduced into identical soil masses to assess their influence on key index properties. The results show a progressive reduction in the Liquid Limit (LL) from 44.00% to 42.01% as lead concentration increased, indicating diminishing soil liquidity. The Plastic Limit (PL) also demonstrates a slight decline, while the Plasticity Index (PI) drops consistently from 14.00% to 13.01%, implying reduced plastic behaviour. Specific Gravity increases steadily from 2.45 to 2.92, reflecting the higher density contribution of lead ions. Moisture Content rises from 20.00% to 22.72%, suggesting enhanced water retention. Overall, these findings indicate a concentration-dependent alteration of soil behaviour driven by the physicochemical interactions between lead salts and the soil matrix.

Table 1
Showing Lead and Soil sample results

Lead (g)	Liquid Limit	Plastic Limit	Plastic Index	Specific Gravity	Moisture Content
10	44	30	14	2.45	20
15	43.25	29.25	14	2.57	20.9
20	42.73	28	13.78	2.68	21.84
25	42.52	29.02	13.5	2.82	22.39
30	42.01	29.02	13.01	2.92	22.72

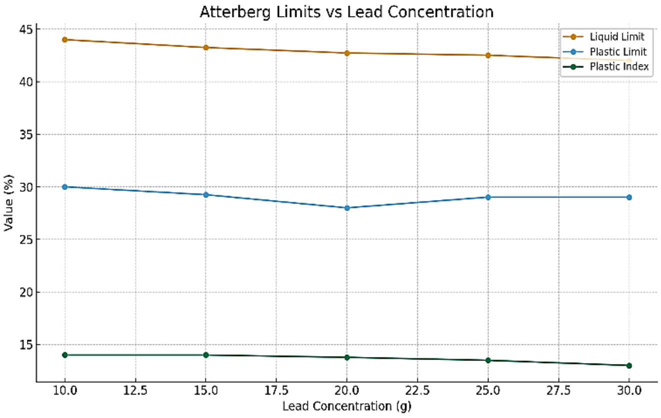

Fig. 1. Atterberg's Limit test

The Atterberg Limits Graph Figure 1 illustrates the relationship between lead contamination levels and changes in the soil's consistency parameters: Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI). As lead concentration increases from 10 g to 30 g, a gradual reduction in LL is observed, indicating reduced water demand for the soil to reach its liquid state. The PL curve shows minor variability but a general downward trend, suggesting a slight reduction in the moisture threshold required for plastic deformation. The PI, representing the range of moisture at which soil exhibits plastic behaviour, decreases steadily, implying that lead contamination restricts the soil's plasticity window. These declining trends collectively demonstrate that lead ions induce particle flocculation and reduce diffuse double-layer thickness, resulting in stiffer, less plastic soil behaviour. The graph therefore highlights the sensitivity of consistency limits to contamination and supports previous findings on heavy-metal-induced alterations of clayey soils.

The graph Figure 2 depicting Specific Gravity (SG) and Moisture Content (MC) variations with increasing lead contamination reveals two contrasting but related behavioural trends. Specific Gravity increases consistently from 2.45 to 2.92 as lead concentration rises, reflecting the incorporation of denser lead ions and the potential formation of heavy-metal precipitates on particle surfaces.

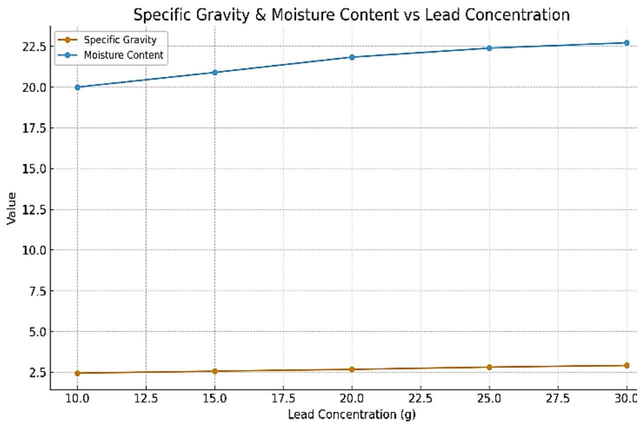

Fig. 2. Specific gravity and Moisture content

This increase suggests a modification of particle density and possible changes in the soil's mineralogical composition. Again, Moisture Content rises from 20.00% to 22.72%, indicating enhanced water-retention capacity in lead-contaminated soils. This behaviour may result from the disruption of soil microstructure, changes in surface chemistry, or increased adsorption associated with ionic interactions between lead and clay minerals. The combined trends demonstrate that lead contamination induces both densification of the soil solids and an alteration of pore-water behaviour. The graph provides clear evidence of concentration-dependent modifications essential for understanding the engineering implications of polluted soils.

The particle size distribution results Table 2 indicate that the soil comprises 57.2% sand, 25.3% silt, and 17.5% clay, reflecting a predominantly sandy matrix with moderate fines content. This gradation suggests a soil that is coarse-textured yet possesses sufficient silt and clay fractions to influence its plasticity and moisture-related behaviour. Based on the USDA textural classification, the soil corresponds to a *loam* or *sandy loam*, while the AASHTO system places it within the A-2 group, typically associated with good to moderate engineering performance. The balanced distribution of sand and fines provides a suitable baseline for assessing contamination-induced changes in index properties.

Table 2
Particle Size Distribution

Soil Fraction	Percentage (%)
Sand	57.2
Silt	25.3
Clay	17.5

4.2 Correlation Analysis

The correlation analysis in Table 3 provides a quantitative assessment of how strongly lead contamination influences each soil index property. The results reveal clear and systematic patterns. Liquid Limit (LL) and Plasticity Index (PI) exhibit strong negative correlations with lead concentration (r = –0.9826 and –0.9416, respectively), indicating that increasing contamination sharply reduces soil liquidity and plastic behaviour. Plastic Limit (PL) demonstrates a weaker negative correlation (r = –0.4841), suggesting that PL is less sensitive to lead-induced changes than LL and PI. Conversely, Specific Gravity (SG) and Moisture Content (MC) show exceptionally strong positive correlations (r = 0.9990 and 0.9819), implying that lead contamination consistently increases particle density and water retention capacity. These high correlation coefficients reflect systematic physicochemical alterations driven by Pb^{2+} interactions with soil particles. The correlation matrix highlights that lead contamination significantly influences the soil's consistency and density-related properties, confirming strong contamination–property dependency.

Table 3
The correlation matrix

Variable	Correlation with Lead (r)
Liquid Limit (LL)	–0.9826
Plastic Limit (PL)	–0.4841
Plastic Index (PI)	–0.9416
Specific Gravity (SG)	0.999
Moisture Content (MC)	0.9819

4.3 Regression Analysis

Table 4.
Linear regression models

Property	Regression Equation	Slope	Intercept	R^2
Liquid Limit (LL)	LL = –0.094x + 44.786	–0.094	44.79	0.965
Plastic Limit (PL)	PL = –0.044x + 29.934	–0.044	29.93	0.234
Plastic Index (PI)	PI = –0.050x + 14.650	–0.050	14.65	0.887
Specific Gravity (SG)	SG = 0.024x + 2.2120	0.024	2.21	0.998
Moisture Content (MC)	MC = 0.137x + 18.798	0.137	18.8	0.964

The regression analysis in Table 4 establishes predictive linear relationships between lead concentration and each soil property. Strong linearity is observed in Liquid Limit ($R^2 = 0.9654$), Plasticity Index ($R^2 = 0.8866$), Specific Gravity ($R^2 = 0.9981$), and Moisture Content ($R^2 = 0.9640$), demonstrating that these parameters can be reliably estimated using simple linear models. These high R^2 values indicate that changes in soil behaviour result directly from the concentration of lead ions modifying soil fabric, density, and water adsorption mechanisms. Plastic Limit exhibits a weak fit ($R^2 = 0.2344$), suggesting a non-linear or weak dependence on lead contamination. The positive regression slopes for SG and MC confirm increasing particle density and moisture retention with rising lead levels, while the negative slopes for LL and PI reflect decreasing plasticity and liquidity. Altogether, the regression models offer a robust analytical basis for predicting contamination-induced variations in soil index properties.

5. Discussion

The results of this study demonstrate clear, concentration-dependent alterations in soil index properties due to lead contamination, reflecting complex physicochemical interactions between Pb^{2+} ions and the soil matrix. The observed decrease in Liquid Limit (LL) and Plasticity Index (PI) with increasing lead concentration aligns with findings that heavy-metal ions suppress diffuse double-layer thickness and promote particle flocculation, thereby reducing soil liquidity and plasticity [27]. As lead ions replace exchangeable cations such as Ca^{2+} and Na^{+}, electrostatic repulsion between clay particles diminishes, resulting in reduced water adsorption capacity [28]. These mechanisms explain the strong negative correlations observed for LL and PI in this study.

The Plastic Limit (PL) exhibited limited systematic variation, suggesting a weaker sensitivity to structural changes compared to LL and PI. Similar irregularity in PL behaviour has been documented for zinc- and cadmium-contaminated soils, where PL remained comparatively stable despite major changes in LL and PI [29]. This indicates that PL may be more dependent on mineralogical composition than on contamination intensity. Studies have shown that PL is largely influenced by the soil's inherent clay type and surface roughness, which are less affected by ionic substitution [30].

The steady increase in Specific Gravity (SG) with lead concentration reflects the contribution of high-density Pb compounds to soil particle mass. This trend corresponds with findings in lead- and arsenic-polluted clays, where SG increased due to heavy-metal precipitation and cation bridging [31]. The nearly perfect linear regression ($R^2 \approx 0.998$) also highlights SG as a reliable indicator of contaminant accumulation, echoing results from environmental monitoring studies [32].

Moisture Content (MC) also increased with lead concentration, which may initially seem counterintuitive given the flocculation-driven reduction in plasticity. However, lead ions alter soil surface chemistry, increasing micropore volume and water-binding capacity through enhanced hydration forces [33]. Additionally, heavy-metal ions form hydration complexes that attract additional water molecules, thereby elevating overall water retention [34]. Recent work has shown that heavy metals can disrupt pore geometry and generate microstructural voids capable of holding higher moisture [35].

Although linear models provided strong fits for LL, PI, SG, and MC, the possibility of non-linear behaviour must be acknowledged. Heavy-metal interactions frequently exhibit threshold responses where initial contamination induces rapid changes, followed by stabilisation at higher concentrations [36]. E.g. PL's weak linearity ($R^2 \approx 0.23$) may indicate polynomial or sigmoidal behaviour, consistent with trends observed in nickel- and chromium-polluted soils [37]. Non-linear adsorption behaviour of heavy metals on clay surfaces has also been reported, supporting the need for alternative modelling approaches [38].

Finally, the multi-faceted influence of lead on soil behaviour has significant engineering implications. Reduced LL and PI indicate increased soil brittleness, potentially affecting compressibility and shear strength. Increased SG and MC imply denser but wetter soils that may undergo differential settlement. These observations align with contemporary research emphasising the need for contamination-aware geotechnical evaluation [39]. Similar studies have stressed that heavy-metal–altered soils exhibit anomalous consolidation behaviour and require modified design parameters [40]. Ultimately, the present findings reinforce the necessity of integrating contamination assessment into foundation design and soil classification frameworks [41].

6. Conclusion

This study has demonstrated that lead contamination exerts a significant and measurable influence on the index properties of soil, revealing clear concentration-dependent behavioural trends with important geotechnical implications. The results show that increasing Pb^{2+} concentrations consistently reduced the Liquid Limit and Plasticity Index, reflecting diminished soil liquidity and plasticity due to the flocculation of clay particles and the suppression of diffuse double-layer effects. These findings provide empirical evidence that lead alters the fundamental consistency behaviour of soil, affecting its ability to deform and respond to moisture variations. The Plastic Limit displayed minimal variation, suggesting that its controlling mechanisms are more strongly governed by intrinsic mineralogical characteristics than by contamination intensity.

Specific Gravity increased markedly with higher contamination levels, confirming that heavy, adsorbed lead ions contribute directly to particle densification. This behaviour aligns with established theories of metal-ion substitution and mineral-surface precipitation, validating the use of Specific Gravity as an indicator parameter for pollution-induced changes in soil solids. Moisture Content also increased progressively, indicating an enhanced water-retention capacity linked to microstructural modifications and hydration effects associated with lead-surface interactions. These combined effects reveal that contaminated soils become simultaneously denser and

wetter, conditions that may influence compressibility, settlement potential, and shear response.
The integration of correlation and regression analyses provided quantitative clarity to the contamination–property relationships. Highly significant linear relationships were observed for Liquid Limit, Plasticity Index, Specific Gravity, and Moisture Content, underscoring the strong predictive capability of these models in assessing contamination impacts. This analytical approach strengthens the scientific basis for using index properties as diagnostic indicators of heavy-metal interference in soils.

On the whole, the study contributes meaningful insights to environmental geotechnics by establishing a structured, concentration-dependent understanding of how lead contamination alters soil behaviour. The findings underscore the necessity for contamination-aware soil classification and foundation assessment, particularly in regions where industrial activities, waste disposal, or informal metal-processing operations pose high contamination risks. By providing experimentally derived relationships and mechanistic explanations, this research offers valuable guidance for engineers, environmental practitioners, and decision-makers responsible for construction planning and remediation in pollution-affected terrains.

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