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An Integrated Soil Assessment Framework For Preliminary Subgrade Characterization

Kerangka Penilaian Tanah Terintegrasi Untuk Karakterisasi Awal Tanah Dasar

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ABSTRACT
Reliable identification of unfavorable subgrade conditions is essential for supporting geotechnical site characterization and infrastructure planning. Conventional investigations commonly evaluate physical, mechanical, or classification parameters separately, whereas engineering behaviour is controlled by the interaction among multiple soil characteristics. This study proposes an Integrated Soil Assessment Framework that combines physical properties, engineering classification, mechanical response, and mineralogical information into a unified interpretation of subgrade soil characteristics. The framework was applied to an industrial development area in East Java, Indonesia, using laboratory and field investigations, including natural water content, grain-size distribution, Atterberg limits, hydraulic conductivity, California Bearing Ratio (CBR), sand cone testing, Unified Soil Classification System (USCS), AASHTO classification, and X-ray diffraction (XRD) analysis. The integrated interpretation identified sampling locations exhibiting weak, moderate, and strong indications of unfavorable subgrade characteristics based on the consistency among multiple engineering indicators. Although all investigated locations satisfied the minimum CBR and compaction requirements, several sampling locations consistently exhibited relatively high plasticity, low hydraulic conductivity, unfavorable AASHTO classifications, and the occurrence of montmorillonite, indicating that satisfactory mechanical performance alone does not necessarily represent favorable subgrade conditions. Spatial interpretation further revealed that these indications occur locally rather than uniformly across the study area, supporting the importance of incorporating spatial variability into preliminary site characterization. The proposed framework provides a practical and transferable approach for integrating complementary geotechnical datasets to improve engineering interpretation and support preliminary geotechnical investigations in heterogeneous soil environments.

Keywords: engineering classification, geotechnical site characterization, integrated soil assessment, mineralogical validation, soil characterization, subgrade soil

ABSTRAK
Identifikasi kondisi tanah dasar yang kurang menguntungkan secara andal merupakan aspek penting dalam mendukung karakterisasi geoteknik dan perencanaan infrastruktur. Investigasi konvensional umumnya mengevaluasi parameter fisik, mekanik, atau klasifikasi tanah secara terpisah, sedangkan perilaku rekayasa tanah dipengaruhi oleh interaksi berbagai karakteristik tanah. Penelitian ini mengusulkan kerangka penilaian tanah terintegrasi (Integrated Soil Assessment Framework) yang menggabungkan sifat fisik, klasifikasi keteknikan, respons mekanik, dan informasi mineralogi untuk menghasilkan interpretasi terpadu terhadap karakteristik tanah dasar. Kerangka penilaian tersebut diterapkan pada kawasan pengembangan industri di Jawa Timur, Indonesia, menggunakan hasil investigasi laboratorium dan lapangan yang meliputi kadar air alami, distribusi ukuran butir, batas Atterberg, konduktivitas hidraulik, California Bearing Ratio (CBR), pengujian kerucut pasir (sand cone), klasifikasi tanah berdasarkan Unified Soil Classification System (USCS) dan AASHTO, serta analisis difraksi sinar-X (X-ray diffraction, XRD). Interpretasi terintegrasi mengidentifikasi lokasi-lokasi pengambilan sampel yang menunjukkan indikasi lemah, sedang, dan kuat terhadap karakteristik tanah dasar yang kurang menguntungkan berdasarkan konsistensi berbagai

indikator keteknikan. Meskipun seluruh lokasi investigasi memenuhi persyaratan minimum CBR dan pemadatan, beberapa lokasi menunjukkan indeks plastisitas yang relatif tinggi, konduktivitas hidraulik yang rendah, klasifikasi AASHTO yang kurang menguntungkan, serta keberadaan mineral montmorilonit. Temuan ini menunjukkan bahwa kinerja mekanik yang memenuhi persyaratan tidak selalu mencerminkan kondisi tanah dasar yang menguntungkan. Interpretasi spasial lebih lanjut memperlihatkan bahwa indikasi tersebut tersebar secara lokal dan tidak merata di seluruh wilayah penelitian, sehingga menegaskan pentingnya mempertimbangkan variasi spasial dalam karakterisasi awal lokasi. Kerangka penilaian yang diusulkan menyediakan pendekatan praktis yang dapat diterapkan pada lokasi lain untuk mengintegrasikan berbagai data geoteknik yang saling melengkapi, meningkatkan interpretasi keteknikan, dan mendukung investigasi geoteknik awal pada lingkungan tanah yang heterogen.

Kata kunci: *klasifikasi keteknikan, karakterisasi geoteknik, penilaian tanah terintegrasi, validasi mineralogi; karakterisasi tanah, tanah dasar*

INTRODUCTION

Infrastructure development requires a thorough understanding of subsurface conditions because the engineering performance and long-term stability of engineering structures are fundamentally controlled by the characteristics of the supporting ground. Comprehensive geotechnical site characterization has therefore become an essential component of infrastructure planning, as inadequate characterization may lead to inappropriate foundation design, excessive settlement, and increased construction risks. Recent studies also emphasize that integrated site characterization improves engineering interpretation by combining complementary sources of subsurface information rather than relying on isolated observations (Akinlalu, Futai, Afolabi, & Abrahama, 2026).

Problematic soils generally refer to soils that exhibit unfavorable engineering characteristics that may adversely affect the performance of engineering structures, such as low bearing capacity, high compressibility, excessive settlement, or significant moisture-induced volume changes. These characteristics may arise from intrinsic soil properties, including the presence of expansive clay minerals, high plasticity, or weak soil structure (Mitchell & Soga, 2005; Budhu, 2011). Consequently, problematic soils remain a major challenge in engineering practice, particularly when their unfavorable characteristics are not adequately identified during site investigation. More recently, Amayreh and Mohamed (2023) highlighted that problematic soils continue to be a major concern in infrastructure development because they frequently require costly ground improvement and may significantly affect long-term structural performance. Consequently, early identification and characterization of problematic soils have become essential components of geotechnical investigations to support reliable engineering design.

The engineering behaviour of problematic soils is controlled by a combination of physical, mechanical, and mineralogical characteristics rather than by a single engineering parameter. Physical properties, including natural water content, grain-size distribution, plasticity index, and hydraulic conductivity, govern soil consistency, drainage behaviour, and deformation potential (Das & Sobhan, 2014). Recent studies have further demonstrated that variations in plasticity and permeability strongly influence the engineering performance of fine-grained soils, confirming their importance in subgrade evaluation (Fatnanta *et al*., 2023; Hassan *et al*., 2023). Mechanical characteristics, commonly represented by California Bearing Ratio (CBR) and field density, provide direct information regarding bearing capacity and compaction quality of subgrade materials (Coduto *et al*., 2011; Katte *et al*., 2019). In addition, standardized engineering classification systems, including the Unified Soil Classification System (USCS) and AASHTO, provide an effective preliminary assessment of engineering suitability based on particle-size distribution and plasticity characteristics (Moreno-Maroto *et al*., 2021). Nevertheless, soil behaviour cannot be fully explained without considering mineralogical composition.

Díaz-López *et al*. (2023) and Elhassan and Mnzool (2023) demonstrated that expansive clay minerals, particularly montmorillonite, play a dominant role in controlling swelling behaviour, strength degradation, and moisture sensitivity. These findings indicate that each soil characterization method describes different aspects of soil behaviour and therefore provides complementary rather than redundant information.

Previous studies have investigated problematic soils using different approaches depending on the engineering objectives. Several researchers have emphasized physical properties, particularly plasticity index, water content, permeability, and grain-size distribution, to evaluate swelling potential and engineering behaviour (Hassan *et al*., 2023; Shi & Li, 2024). Other studies have focused primarily on mechanical properties, such as CBR and field density, to assess the suitability of soils as subgrade materials (Katte *et al*., 2019). Mineralogical analyses using X-ray diffraction (XRD) have also been widely employed to explain the occurrence of expansive behaviour through the identification of clay minerals (Díaz-López *et al*., 2023). Although these approaches have substantially improved the understanding of problematic soils, they generally evaluate each parameter independently. Recent developments in geotechnical site characterization indicate a growing trend toward integrating multiple complementary datasets to reduce interpretation uncertainty and improve engineering decision-making. However, studies that systematically integrate physical properties, engineering classification, mechanical characteristics, and mineralogical evidence into a unified framework for assessing subgrade soils remain limited.

This study proposes an integrated assessment of subgrade soil characteristics by systematically combining physical properties, mechanical characteristics, engineering classification, and mineralogical information into a unified evaluation framework. The proposed assessment is demonstrated through a case study conducted in an industrial development area, where multiple soil characterization datasets are integrated to identify locations exhibiting stronger indications of unfavorable subgrade characteristics and to evaluate their spatial distribution. Unlike conventional approaches that rely on individual engineering parameters, the integrated assessment presented in this study provides a more comprehensive basis for geotechnical site characterization by considering the complementary roles of each soil property. The proposed framework is expected to support preliminary engineering decision-making and may serve as a practical approach for evaluating subgrade soils in areas with heterogeneous geological conditions.

RESEARCH METHODS

The study was conducted in an industrial development area in East Java, Indonesia. The exact site location is not disclosed due to confidentiality requirements associated with the industrial development project. A geotechnical site investigation was conducted to evaluate the engineering characteristics of subgrade soils prior to infrastructure development. Comprehensive site characterization is essential in engineering projects because the performance of foundations and earth structures is strongly influenced by the spatial variability of subsurface conditions. The study area is characterized by heterogeneous near-surface deposits that potentially exhibit contrasting engineering properties, thereby requiring representative sampling and laboratory characterization to adequately capture local variability (Budhu, 2011; Das & Sobhan, 2014).

A total of fourteen disturbed soil samples were collected from representative locations distributed across the study area. Sampling locations were selected to represent the spatial variability of surface soils within the planned development zone. In addition, in-situ California Bearing Ratio (CBR) and Sand Cone tests were conducted at selected locations to evaluate the bearing capacity and field compaction characteristics

of the subgrade soils. The distribution of soil sampling locations and field-testing stations is presented in Figure 1.

Soil Characterization. Subgrade soils were characterized using four complementary groups of engineering parameters, namely physical properties, mechanical characteristics, engineering classification, and mineralogical composition, to support the proposed Integrated Soil Assessment Framework. This multi-parameter characterization was designed to provide a comprehensive understanding of soil behaviour because each parameter represents different aspects of engineering performance and contributes complementary information for engineering interpretation (Mitchell & Soga, 2005; Budhu, 2011).

Physical characterization included the determination of natural water content, grain-size distribution, Atterberg limits, and hydraulic conductivity. These parameters describe soil consistency, permeability, and deformation potential and are commonly used as preliminary indicators of engineering behaviour (Das & Sobhan, 2014; Knappett & Craig, 2012). Recent studies further demonstrate that plasticity and hydraulic conductivity strongly influence the engineering performance of fine-grained soils and therefore represent important indicators for subgrade evaluation (Fatnanta *et al*., 2023; Hassan *et al*., 2023). Mechanical characterization consisted of in-situ California Bearing Ratio (CBR) and Sand Cone tests to evaluate soil bearing capacity and field compaction characteristics. These parameters directly represent the engineering response of subgrade soils under loading conditions and are widely adopted in pavement and geotechnical investigations (Coduto, 1999; Katte *et al*., 2019).

Engineering classification was subsequently performed using the Unified Soil Classification System (USCS) and the AASHTO classification system. Both systems provide standardized

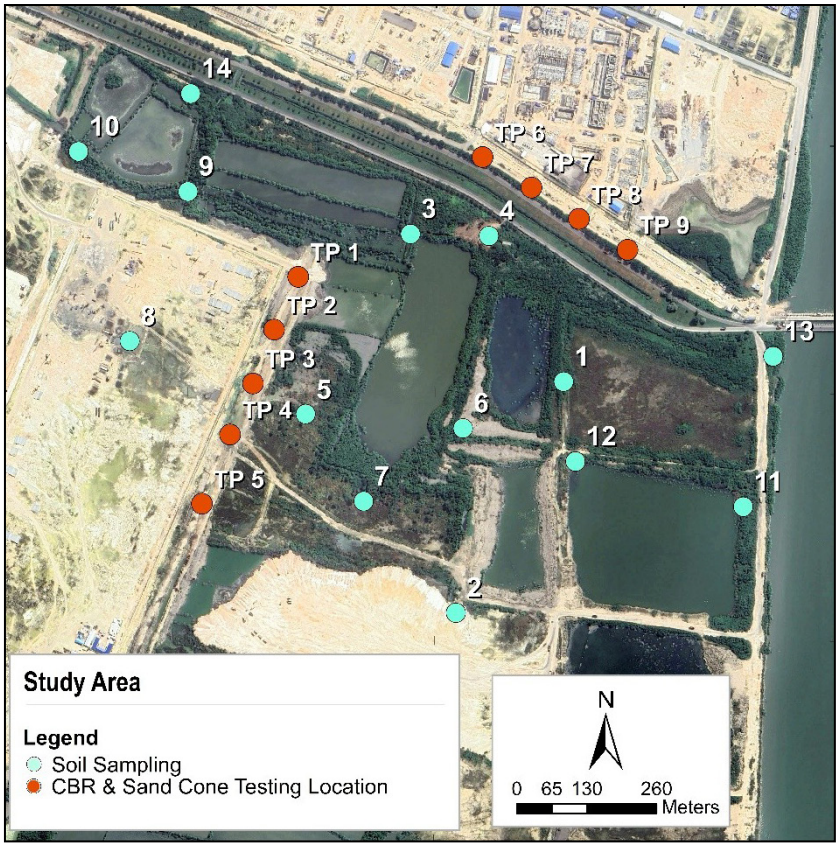


Figure 1. Location of soil sampling points and field-testing stations (CBR and Sand Cone) within the study area.

descriptions of engineering materials based on particle-size distribution and plasticity characteristics and remain widely adopted in geotechnical engineering practice (ASTM D2487; AASHTO M145; Moreno-Maroto *et al*., 2021). Mineralogical characterization was conducted using X-ray diffraction (XRD) to identify the mineral phases present in representative soil samples. XRD measurements were performed using a Rigaku MiniFlex diffractometer with Cu radiation as the X-ray source. Diffraction patterns were recorded over a 2θ range of 3–90°, using a scan speed of 10°/min and a step width of 0.02°. The resulting diffraction patterns were used to identify the mineral assemblages, with particular attention to the occurrence of expansive clay minerals such as montmorillonite. Mineralogical characterization provides complementary information that cannot be obtained from conventional index properties alone because expansive clay minerals can strongly influence swelling behaviour, plasticity, and strength characteristics of fine-grained soils (Díaz-López *et al*., 2023; Elhassan & Mnzool, 2023). Laboratory and field-testing procedures followed internationally recognized standards as summarized in Table 1.

The proposed Integrated Soil Assessment Framework was developed to provide a comprehensive evaluation of subgrade soil characteristics by systematically integrating complementary geotechnical datasets into a unified engineering interpretation. Rather than relying on a single engineering parameter, the framework integrates physical properties, mechanical characteristics, and engineering classification, with mineralogical information subsequently used to support and validate the engineering interpretation, thereby reducing uncertainty in preliminary site characterization. This concept is consistent with recent developments in geotechnical site characterization, which emphasize the integration of multiple sources of subsurface information to improve engineering interpretation and reduce uncertainty associated with heterogeneous ground conditions (Li *et al*., 2025).

Within the proposed framework, grain-size distribution represents an intrinsic characteristic of the soil material, whereas natural water content, plasticity index, and hydraulic conductivity describe its physical behaviour. Mechanical parameters, including California Bearing Ratio (CBR) and field density, represent the engineering response of the soil under loading conditions. Engineering classifications based on USCS and AASHTO provide additional standardized interpretations of engineering suitability. No numerical weighting was assigned to the individual parameters. Instead, the framework employs a rule-based multiple-lines-of-evidence approach, in which the parameters are treated as complementary indicators representing different aspects of subgrade soil behaviour. The engineering significance of these indicators was evaluated collectively based on the degree of consistency, or convergence, of unfavorable evidence across the physical properties, engineering classifications, and mechanical response. Accordingly, the integrated interpretation was not derived from a weighted numerical average or from any single parameter. Such integrated interpretation is increasingly recognized as an effective strategy

Table 1. Summary of laboratory and field tests.

Group	Parameter	Standard	Purpose in Integrated Assessment
Physical	Water Content	ASTM D2216	Moisture condition
Physical	Grain Size	ASTM D6913	Soil texture
Physical	Atterberg Limits	ASTM D4318	Plasticity
Physical	Permeability	ASTM D2434 / D5084	Drainage
Mechanical	CBR	ASTM D4429	Bearing capacity
Mechanical	Sand Cone	ASTM D1556	Field density
Classification	USCS	ASTM D2487	Engineering classification
Classification	AASHTO	M145	Subgrade suitability
Mineralogical	XRD	ASTM D934	Clay mineral identification

for geotechnical site characterization because it combines complementary observations to produce more robust engineering assessments than individual datasets alone (Olayanju, 2017). To ensure consistency and reproducibility of the integrated interpretation, the engineering role and decision criteria applied to the evaluated parameters were explicitly defined, as summarized in Table 2. Established geotechnical criteria and guidelines were adopted where applicable, whereas parameters for which no universally applicable performance threshold exists were retained as complementary evidence rather than assigned arbitrary numerical scores.

Based on the parameter roles and decision criteria defined in Table 2, the integrated indication level was assigned according to the operational rules summarized in Table 3.

The indication levels in Table 3 represent study-specific engineering interpretations developed within the proposed framework rather than standardized geotechnical soil classes. Mineralogical information obtained from XRD was not included in the initial indication assignment but was subsequently used as independent evidence to support or validate the engineering interpretation. The resulting integrated interpretation was subsequently used to identify sampling locations exhibiting different levels of indication of unfavorable subgrade characteristics prior to spatial interpretation. The conceptual workflow of the proposed Integrated Soil Assessment Framework is illustrated in Figure 2.

The integrated assessment results were subsequently interpreted in a spatial context to examine the spatial variability of subgrade soil characteristics across the study area. Engineering interpretations obtained at each sampling location were linked with their geographic coordinates using a Geographic Information System (GIS). Spatial visualization was generated using the Inverse Distance Weighting (IDW) interpolation method, in which estimated values at unsampled locations are calculated as weighted averages of nearby observations, with closer samples exerting greater influence than more

Table 2. Decision criteria and roles of geotechnical parameters used for the rule-based Integrated Soil Assessment Framework

Indicator	Decision criterion	Role	Basis/Reference
PI	<25% = Low; 25–35% = Marginal; >35% = High expansion potential	Direct	AASHTO T258; FHWA (2007)
AASHTO	A-1–A-3 = generally favorable; A-4–A-7 = increasing subgrade concern	Direct	AASHTO M145
CBR	CBR: ≥6% = meets; <6% = does not meet project requirement; unavailable = not evaluated	Direct	FHWA (2007)
Grain-size distribution, WC, K, USCS	No independent concern threshold was applied; these parameters were interpreted as complementary information describing soil composition, moisture condition, hydraulic behaviour, and engineering soil type.	Supporting	FHWA (2007)
XRD	Mineral assemblage evaluated after the initial engineering assessment	Validation	Díaz-López *et al*. (2023); Elhassan and Mnzool (2023)

Tabel 3. Operational rules for assigning the integrated indication levels of unfavorable subgrade characteristics based on the available direct and supporting indicators

Final indication	Operational rule	Interpretation
Weak	Available direct indicators predominantly indicate favorable conditions, with no clear convergence of marginal or unfavorable evidence.	Limited evidence of unfavorable subgrade characteristics
Moderate	One available direct indicator indicates marginal or unfavorable conditions, or mixed evidence occurs among the available direct indicators.	Partial or inconsistent evidence of unfavorable subgrade characteristics
Strong	At least two available direct indicators indicate marginal or unfavorable conditions, supported by complementary evidence showing an unfavorable pattern.	Convergent evidence of unfavorable subgrade characteristics

Note: Where a direct indicator was unavailable, it was treated as not evaluated rather than as favorable or unfavorable, and the indication level was determined from the remaining available direct indicators.

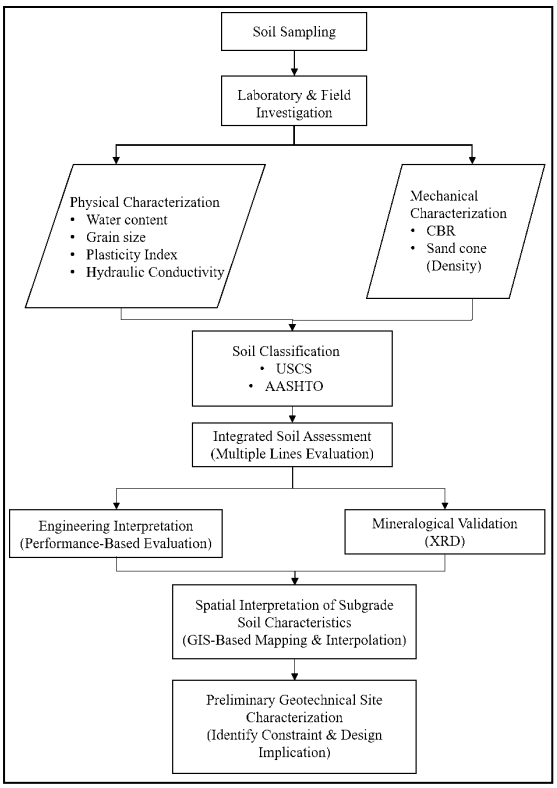


Figure 2. Conceptual framework of the Integrated Soil Assessment proposed in this study. Physical properties, mechanical characteristics, engineering classification, and mineralogical validation are collectively interpreted to provide a comprehensive assessment of subgrade soil characteristics and their spatial distribution.

distant samples (Burrough & McDonnell, 1998).

Considering the relatively limited number of sampling locations, IDW was selected as a deterministic interpolation technique to visualize localized spatial variability without assuming an underlying statistical model. The interpolated surfaces were used solely to illustrate the spatial distribution of integrated assessment results and to facilitate comparison among different parts of the study area. They were not intended to predict subsurface conditions beyond the investigated sampling locations.

Spatial visualization supports engineering interpretation by relating geotechnical characteristics to their geographic distribution and assists in identifying localized zones that may require more detailed geotechnical investigation during future infrastructure development (Longley *et al*., 2015).

RESULTS AND DISCUSSION

The physical characterization results demonstrate considerable variability in the engineering properties of the investigated soils, indicating heterogeneous subgrade conditions within the study area (Table 4). Natural water content ranged from 0.10% to 72.88%, while the plasticity index (PI) varied from non-plastic (NP) to 29%. Hydraulic conductivity also exhibited a wide range, from 8.02×10^{-6} cm/s to 1.55×10^{-2} cm/s, reflecting substantial differences in drainage characteristics among the investigated sampling locations.

Grain-size analysis revealed noticeable differences between the dry and wet sieving methods. Dry sieving indicated that most samples were dominated by sand-sized particles (>83%), whereas wet sieving identified substantially higher proportions of fine-grained materials in several samples. This difference is attributed to the dispersion of aggregated clay particles during wet sieving, which remain attached to coarser grains during dry sieving. Consequently, wet sieving provides a more representative estimation of the fine-grained fraction in cohesive soils and therefore offers a more reliable basis for subsequent engineering classification and interpretation. Similar observations were reported by Ma and Song (2023), who demonstrated that wet sieving improves the characterization of soils containing aggregated clay particles.

The Atterberg limits indicate that several samples exhibit moderate to high plasticity, with plasticity index values reaching 29%, suggesting relatively active fine-grained constituents. According to Mitchell and Soga (2005), increasing plasticity generally reflects greater clay activity and higher susceptibility to moisture-induced deformation. Samples exhibiting relatively high plasticity also tend to possess lower hydraulic conductivity, indicating that increasing fine-grained content reduces pore connectivity and restricts water movement through the soil matrix (Das & Sobhan, 2014).

Table 4. Summary of physical characterization results of the investigated soil samples

Soil Sample	Wc (%)	*Dry Sieving*			*Wet Sieving*		LL (%)	PL (%)	IP (%)	K (cm/s)
		Gravel (%)	Sand (%)	Silt & Clay (%)	Gravel & Sand (%)	Silt & Clay (%)				
1	1.40	1.54	95.11	3.36	16.41	83.59	61	32	29	1.30×10^{-4}
2	0.50	1.32	86.49	12.19	82.67	17.33	NP	NP	NP	1.55×10^{-2}
3	72.88	0.92	94	5.08	16.69	83.31	46	35	12	1.13×10^{-4}
4	2.98	0.22	96.91	2.87	71.35	28.65	NP	NP	NP	7.08×10^{-3}
5	2.08	3.43	92.15	4.43	75.32	24.68	43	21	22	1.37×10^{-3}
6	0.47	0.28	88.67	11.05	64.57	35.43	26	18	8	1.97×10^{-3}
7	35.73	0.42	93.84	5.74	33.81	66.19	37	30	7	1.13×10^{-4}
8	0.10	14.96	83.16	1.88	99.30	0.70	NP	NP	NP	1.10×10^{-2}
9	3.23	0.67	96	3.32	26.47	73.53	64	36	28	2.25×10^{-4}
10	1.65	0.04	96.45	3.50	28.41	71.59	68	41	28	3.66×10^{-4}
11	39.20	1.88	93.49	4.64	15.42	84.58	39	31	7	2.02×10^{-4}
12	5.71	2.37	92.49	5.14	63.18	36.82	49	29	20	7.37×10^{-5}
13	23.81	6.98	90.34	2.69	55.38	44.62	49	25	24	8.95×10^{-6}
14	37.82	2.22	92.79	4.98	22.03	77.97	54	29	25	8.02×10^{-6}

**Note*: *Wc = Water Content, LL = Liquid Limit, PL = Plasticity Limit, IP = Plasticity Index, K = Hydraulic Conductivity, NP = Non-plastic.*

The relationships between hydraulic conductivity and plasticity index (Figure 3a), as well as between hydraulic conductivity and the fine-grained fraction (Figure 3b), illustrate a general inverse trend in which hydraulic conductivity decreases as plasticity and fine-grained content increase. Although considerable scatter is observed due to the natural heterogeneity of the investigated soils, the overall tendency agrees with previously reported empirical relationships proposed by Sridharan (2005) and Siswosoebrotho (2005). These observations indicate that both plasticity and fine-grained content are important indicators controlling the hydraulic behaviour of subgrade soils and provide complementary information for the integrated assessment developed in this study.

The engineering classification results indicate

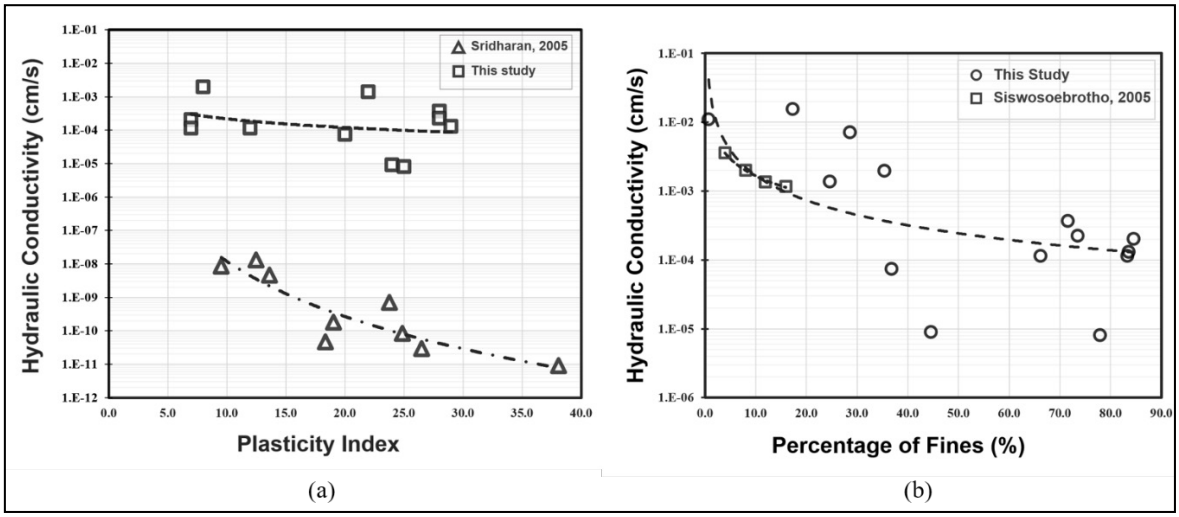


Figure 3. Comparison of the relationships between hydraulic conductivity and (a) plasticity index and (b) fine-grained fraction obtained in this study with previously reported empirical relationships.

that most soil samples are classified as well-graded sand (SW) or well-graded sand with silt (SW–SM) according to the Unified Soil Classification System (USCS), as summarized in Table 5. These classifications are primarily derived from particle-size distribution determined by dry sieving and therefore describe the dominant coarse-grained fraction of the investigated soils.

In contrast, the AASHTO classification based on wet sieving assigns several samples to the A-7-6 group, which is generally associated with clay-rich subgrade materials exhibiting relatively poor engineering performance. The discrepancy between the USCS and AASHTO classifications reflects the influence of fine-grained particles that become more evident after wet sieving disperses aggregated clay particles. Similar observations were reported by Ma and Song (2023), who demonstrated that wet sieving provides a more representative estimation of the fine-grained fraction in cohesive soils. These findings suggest that engineering classification can vary considerably depending on the method used to characterize particle-size distribution and highlight the importance of adequately dispersing cohesive particles before classification.

Despite the occurrence of several samples exhibiting relatively unfavorable physical characteristics and engineering classifications, field mechanical characterization indicates that all investigated locations satisfy the minimum engineering requirements for subgrade construction (Table 6). California Bearing Ratio (CBR) values range from 16.4% to 31.8%, considerably exceeding the commonly adopted minimum requirement of 6% for subgrade materials, while field density values range from 96.5% to 99.7%, all exceeding the minimum compaction requirement of 95%.

These results indicate that satisfactory mechanical performance under existing field conditions does not necessarily imply favorable intrinsic soil characteristics. Mechanical properties primarily describe the current engineering response of the soil under loading and compaction conditions, whereas physical properties and engineering classification provide information regarding the inherent characteristics of the soil material and its potential response to environmental changes. Consequently, interpreting mechanical characteristics independently may lead to an incomplete understanding of subgrade behav-

Table 5. Engineering classification of the investigated soil samples based on the Unified Soil Classification System (USCS) and AASHTO classification using dry and wet sieving results

Soil Sample	*Dry Sieving*			*Wet Sieving*		LL	IP	USCS (*dry sieving*)	AASHTO (*dry sieving*)	AASHTO (*wet sieving*)
	Gravel (%)	Sand (%)	Silt & Clay (%)	Gravel & Sand (%)	Silt & Clay (%)					
1	1.54	95.11	3.36	16.41	83.59	61	29	SW	A-2-7	A-7-6
2	1.32	86.49	12.19	82.67	17.33	NP	NP	SW-SM	A-1-b	A-3
3	0.92	94	5.08	16.69	83.31	46	12	SP-SM	A-2-7	A-7-6
4	0.22	96.91	2.87	71.35	28.65	NP	NP	SP	A-3	A-3
5	3.43	92.15	4.43	75.32	24.68	43	22	SW	A-2-7	A-2-7
6	0.28	88.67	11.05	64.57	35.43	26	8	SP-SC	A-2-4	A-2-4
7	0.42	93.84	5.74	33.81	66.19	37	7	SW-SM	A-2-4	A-4
8	14.96	83.16	1.88	99.30	0.70	NP	NP	SW	A-1-b	A-3
9	0.67	96	3.32	26.47	73.53	64	28	SW	A-2-7	A-7-6
10	0.04	96.45	3.50	28.41	71.59	68	28	SW	A-2-7	A-7-6
11	1.88	93.49	4.64	15.42	84.58	39	7	SW	A-2-4	A-4
12	2.37	92.49	5.14	63.18	36.82	49	20	SW-SM	A-2-7	A-7-6
13	6.98	90.34	2.69	55.38	44.62	49	24	SW	A-2-7	A-7-6
14	2.22	92.79	4.98	22.03	77.97	54	25	SW-SC	A-2-7	A-7-6

Note: LL = Liquid Limit, IP = Plasticity Index, NP = Non-plastic.

Table 6. Summary of in-situ mechanical characterization, including California Bearing Ratio (CBR) and field density measurements, compared with the minimum engineering requirements for subgrade materials

Measurement Point	CBR (%)	Minimum CBR Requirement for Subgrade (%)	Field Density (%)	Minimum Field Density for Subgrade (%)
TP 1	16.4	6	99.4	95
TP 2	19.2	6	98.9	95
TP 3	17.8	6	96.5	95
TP 4	19.6	6	99.5	95
TP 5	24.1	6	99.7	95
TP 6	27.3	6	98.8	95
TP 7	26.2	6	99.6	95
TP 8	31.8	6	98.2	95
TP 9	31.1	6	99.1	95

iour, highlighting the need for an integrated interpretation that combines complementary geotechnical parameters.

The integrated interpretation combines the results of physical characterization, engineering classification, and mechanical response to provide a unified evaluation of subgrade soil characteristics. Rather than interpreting each engineering parameter independently, the proposed framework evaluates the consistency among multiple complementary indicators to identify sampling locations exhibiting different levels of indication of unfavorable subgrade characteristics. This approach follows the principle that integrating complementary geotechnical information reduces interpretation uncertainty and provides a more reliable basis for site characterization than relying on individual engineering parameters (Li *et al*., 2025).

The integrated assessment summarized in Table 7 demonstrates that several sampling locations consistently exhibit combinations of relatively high natural water content, high plasticity index, low hydraulic conductivity, and less favorable AASHTO classifications. Although each parameter individually provides only partial information regarding soil behaviour, their combined occurrence strengthens the interpretation that these locations possess less favorable subgrade characteristics. This observation is consistent with previous studies showing that engineering behaviour is governed by the interaction among multiple physical and mechanical characteristics rather than by any single soil property (Mitchell & Soga, 2005; Budhu, 2011).

An important outcome of the integrated interpretation is the consistency observed between engineering classification and physical properties. Samples classified as A-7-6 based on the AASHTO system generally correspond to relatively high plasticity indices, reduced hydraulic conductivity, and elevated natural water contents, whereas samples classified as A-3 or A-2-4 generally exhibit lower plasticity and higher hydraulic conductivity. Such agreement indicates that the engineering classification is supported by independent physical characterization rather than representing an isolated observation, which

Table 7. Integrated interpretation of subgrade soil characteristics based on the rule-based assessment criteria

Soil Sample	PI criterion	AASHTO indication	CBR criterion	Integrated indication
1	Marginal	Concern	Meets requirement	**Strong**
2	Low (NP)	Favorable	Meets requirement	**Weak**
3	Low	Concern	Meets requirement	**Moderate**
4	Low (NP)	Favorable	Meets requirement	**Weak**
5	Low	Favorable	Meets requirement	**Weak**
6	Low	Favorable	Meets requirement	**Weak**
7	Low	Concern	Meets requirement	**Moderate**
8	Low (NP)	Favorable	Meets requirement	**Weak**
9	Marginal	Concern	Meets requirement	**Strong**
10	Marginal	Concern	Not evaluated	**Strong**
11	Low	Concern	Not evaluated	**Moderate**
12	Low	Concern	Not evaluated	**Moderate**
13	Low	Concern	Not evaluated	**Moderate**
14	Marginal	Concern	Not evaluated	**Strong**

is consistent with the role of engineering classification systems as preliminary indicators of soil behaviour (Moreno-Maroto *et al*., 2021).

Field mechanical characterization, however, presents a different perspective. Although all investigated locations satisfy the minimum requirements for California Bearing Ratio (CBR) and field compaction, several of these locations simultaneously exhibit less favorable physical characteristics and engineering classifications. This apparent discrepancy indicates that satisfactory short-term mechanical performance does not necessarily represent the overall engineering behaviour of subgrade soils. Mechanical parameters primarily describe the response of the soil under existing field conditions, whereas physical properties and engineering classification provide information regarding the intrinsic characteristics of the soil material and its potential response to environmental changes (Mitchell & Soga, 2005; Budhu, 2011). Consequently, interpreting mechanical performance alone may lead to an incomplete evaluation of subgrade conditions.

X-ray diffraction (XRD) analysis was conducted on representative soil samples to provide independent mineralogical validation of the engineering interpretation obtained from the proposed Integrated Soil Assessment Framework. Representative samples were selected from locations exhibiting different levels of engineering indication to examine whether the interpreted subgrade characteristics were supported by their mineralogical composition. The analysis revealed two contrasting mineral assemblages among the investigated samples (see Table 8). Samples exhibiting strong indications of unfavorable subgrade characteristics were consistently associated with the presence of montmorillonite, whereas samples exhibiting weak indications were dominated by carbonate minerals, particularly dolomite and calcite.

Representative XRD patterns further illustrate the contrasting mineralogical characteristics between soils exhibiting weak and strong engineering indications (Figure 4). Sample 2 is

Table 8. Representative X-ray diffraction (XRD) results used for mineralogical validation of the Integrated Soil Assessment Framework

Soil Sample	Major Mineral Assemblage	Expansive Clay Mineral	Integrated Interpretation
1	Quartz, Albite, Montmorillonite	Montmorillonite	Strong indication
2	Dolomite	None detected	Weak indication
6	Dolomite, Calcite	None detected	Weak indication
7	Montmorillonite	Montmorillonite	Strong indication
9	Albite, Montmorillonite	Montmorillonite	Strong indication
11	Montmorillonite	Montmorillonite	Strong indication

dominated by dolomite, indicating the absence of expansive clay minerals and supporting its relatively favorable engineering characteristics. In contrast, Sample 7 exhibits distinct diffraction peaks corresponding to montmorillonite together with quartz and albite. The occurrence of montmorillonite provides independent mineralogical evidence supporting the engineering interpretation derived from the combined physical characteristics, engineering classification, and mechanical response.

According to Mitchell and Soga (2005), montmorillonite possesses a high specific surface area and exceptional water adsorption capacity, making it one of the principal clay minerals responsible for swelling behaviour, increased plasticity, and reduced hydraulic conductivity. The occurrence of montmorillonite is therefore consistent with the relatively high plasticity indices and low hydraulic conductivity observed in Samples 1, 7, 9, and 11. Similar relationships between expansive clay minerals and engineering behaviour have also been reported by Díaz-López *et al*. (2023), who demonstrated that mineralogical composition exerts a fundamental control on the deformation and strength characteristics of fine-grained soils.

In contrast, Samples 2 and 6 are dominated by dolomite and calcite without detectable montmorillonite. Unlike expansive clay minerals, these carbonate minerals possess relatively low specific surface areas and limited affinity for water adsorption, resulting in comparatively stable volume-change behaviour and lower plasticity. Consequently, these samples exhibit

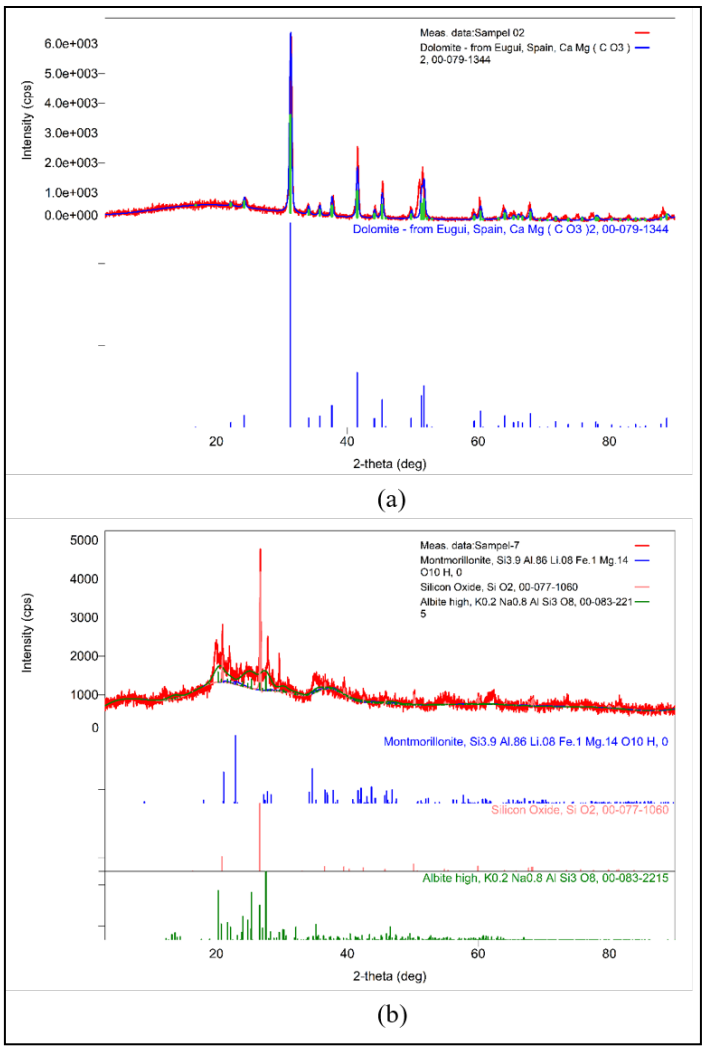


Figure 4. Representative X-ray diffraction (XRD) patterns illustrating the contrasting mineralogical characteristics of (a) Sample 2, dominated by dolomite and representing a weak indication of unfavorable subgrade characteristics, and (b) Sample 7, characterized by the presence of montmorillonite and representing a strong indication of unfavorable subgrade characteristics.

relatively higher hydraulic conductivity and more favorable engineering characteristics, consistent with their weak indications obtained from the integrated assessment.

Overall, the XRD results provide independent mineralogical evidence supporting the engineering interpretation developed through the proposed Integrated Soil Assessment Framework. Rather than functioning as an independent classification technique, XRD complements the physical characterization, engineering classification, and mechanical response by confirming the presence or absence of expansive clay minerals. The close agreement between the mineralogical observations and the integrated interpretation demonstrates that combining mineralogical information with conventional geotechnical characterization improves the reliability of preliminary subgrade assessment and provides a more robust basis for engineering decision-making than relying on individual engineering parameters alone.

The engineering interpretation obtained from the Integrated Soil Assessment Framework was subsequently examined in a spatial context to illustrate the distribution of subgrade characteristics across the investigated area (Figure 5). Rather than representing the spatial distribution of individual geotechnical parameters, the map integrates the engineering interpretation

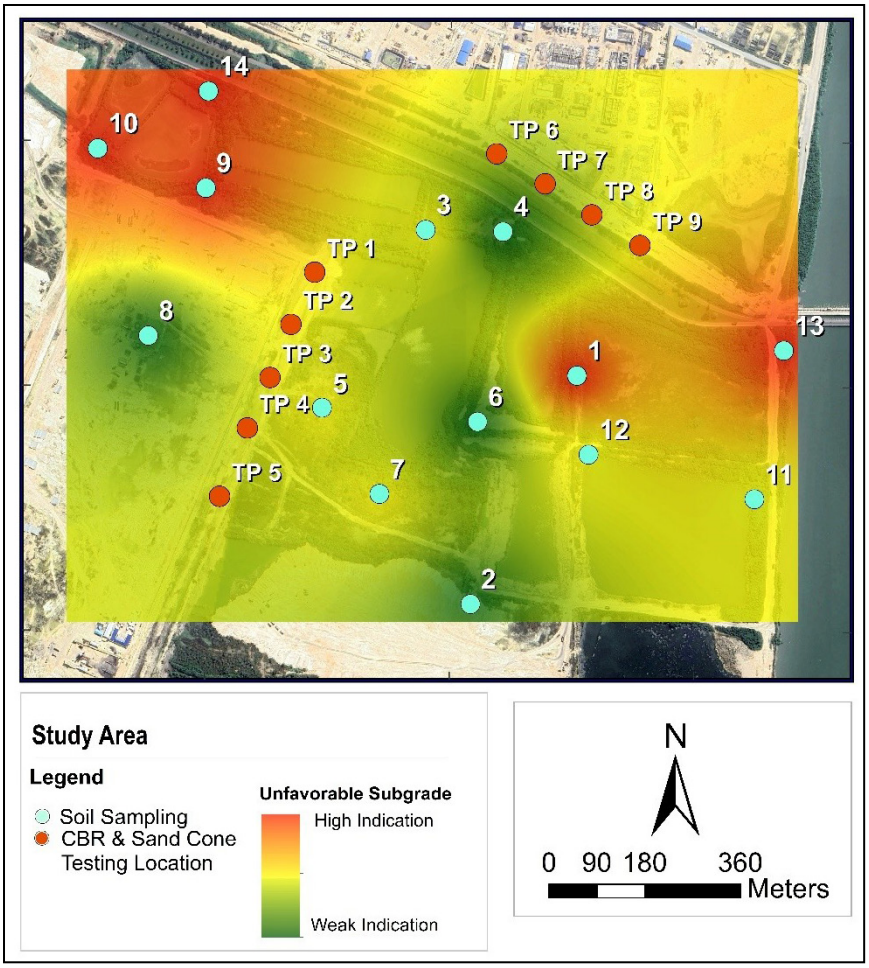


Figure 5. Spatial distribution of the integrated assessment results showing weak, moderate, and strong indications of unfavorable subgrade characteristics derived from the combined interpretation of physical characteristics, engineering classification, mechanical response, and mineralogical validation.

derived from physical characteristics, engineering classification, mechanical response, and mineralogical validation into a unified spatial representation. This approach enables localized variations in subgrade characteristics to be interpreted more comprehensively than by considering individual datasets separately.

The spatial distribution reveals that sampling locations exhibiting strong indications of unfavorable subgrade characteristics are primarily concentrated in the northwestern and eastern parts of the study area. These locations consistently correspond to relatively high plasticity indices, low hydraulic conductivity, less favorable AASHTO classifications, and the occurrence of montmorillonite in representative samples. In contrast, weak indications are predominantly associated with the central and southwestern parts of the study area, where lower plasticity, higher hydraulic conductivity, more favorable engineering classifications, and the absence of expansive clay minerals are generally observed. Several sampling locations exhibit moderate indications, representing transitional engineering characteristics between these two conditions.

It should be emphasized that the interpolated map is intended to illustrate the relative spatial variability of the integrated engineering interpretation rather than to predict subsurface conditions beyond the investigated sampling locations. Consequently, the mapped indication levels should be interpreted as an aid for preliminary geotechnical evaluation and not

as deterministic boundaries between different soil types. Similar considerations have been emphasized in spatial analyses of geotechnical data, where interpolation is primarily intended to support engineering interpretation rather than replace site-specific investigation (Burrough & McDonnell, 1998; Longley *et al*., 2015).

The observed spatial variability demonstrates that unfavorable subgrade characteristics occur locally rather than uniformly throughout the investigated area. From an engineering perspective, this finding highlight that geotechnical site characterization should account for localized variations in soil behaviour during preliminary investigation, particularly in industrial development areas where foundation performance and earthwork design may be influenced by relatively limited zones exhibiting less favorable subgrade characteristics. By integrating multiple complementary datasets into a single spatial interpretation, the proposed framework provides a practical means of identifying areas that warrant more detailed geotechnical investigation before infrastructure development.

CONCLUSIONS

This study demonstrates that interpreting subgrade soils through the integration of physical characteristics, engineering classification, mechanical response, and mineralogical information provides a more comprehensive understanding of engineering behaviour than evaluating individual geotechnical parameters independently. The proposed Integrated Soil Assessment Framework successfully combines multiple complementary datasets into a unified engineering interpretation, allowing subgrade conditions to be evaluated from different but mutually supporting perspectives.

The integrated assessment reveals that satisfactory field mechanical performance alone does not necessarily represent favorable subgrade conditions. Although all investigated locations satisfy the minimum requirements for California Bearing Ratio (CBR) and field compaction, several sampling locations consistently exhibit stronger indications of unfavorable subgrade characteristics when physical properties, engineering classification, and mineralogical evidence are interpreted collectively. Independent X-ray diffraction (XRD) analysis further supports this interpretation by confirming the occurrence of montmorillonite in representative samples exhibiting less favorable engineering characteristics.

Rather than replacing conventional geotechnical investigations, the proposed framework enhances the interpretation of existing laboratory and field data through a multiple-lines-of-evidence approach. The subsequent spatial interpretation further facilitates the recognition of localized variations in subgrade characteristics and provides practical support for preliminary geotechnical site characterization and planning of future site investigations. Although demonstrated using a case study from an industrial development area, the proposed framework is transferable to other heterogeneous soil environments where engineering decisions should be supported by multiple complementary sources of geotechnical information.

REFERENCES

Akinlalu, A., Futai, M., Afolabi, D., & Abrahama, R. (2026). A Review on The Application of Geophysical Methods in Civil Engineering Studies. *Geosystems and Geoenvirontment, 5*(1). doi:10.1016/j.geogeo.2025.100453

Amayreh, L., & Mohamed, M. (2023). Engineering Properties and Mechanical Behaviour of Problematic Soil Stabilized by Bituminous Oil Shale Ash. *Applications in Engineering Science, 16*. doi:10.1016/j.apples.2023.100156

American Association of State Highway and Transportation Officials (AASHTO). (2021). Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes (AASHTO M 145).

ASTM International. (2020). *ASTM D2216-19: Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass.* West Conshohocken: PA: ASTM International.

ASTM International. (2020). *ASTM D4318-17e1: Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.* West Conshohocken: PA: ASTM International.

ASTM International. (2021). *ASTM D6913/D6913M-17: Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis.* West Conshohocken: PA: ASTM International.

ASTM International. (2022). *Standard practices for identification of crystalline compounds in water-formed deposits by X-ray diffraction (ASTM D934-22).* PA: ASTM International.

ASTM International. (2022). *Standard test method for permeability of granular soils (constant head) (ASTM D2434-22).* West Conshohocken: PA: ASTM International.

ASTM International. (2022). *Standard test methods for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter (ASTM D5084-22).* West Conshohocken: PA: ASTM International.

ASTM International. (2023). *Standard test method for density and unit weight of soil in place by sand-cone method (ASTM D1556-23).* West Conshohocken: PA: ASTM International.

ASTM International. (2024). *Standard practice for classification of soils for engineering purposes (Unified Soil Classification System) (ASTM D2487-24).* West Conshohocken: PA: ASTM International.

Budhu, M. (2011). *Soil Mechanics and Foundations 3rd Edition.* Hoboken: John Wiley & Sons, Inc.

Burrough, P. M. (1998). *Principles of Geographical Information Systems.* Oxford: Oxford University Press.

Coduto, D. P. (1999). *Geotechnical Engineering Principles and Practices.* New Jersey: ALAN APT.

Das, B. M., & Sobhan, K. (2014). *Principles of Geotechnical Engineering Eight Edition.* Massachusetts: Cengage Learning.

Díaz-López, J. L. (2023). Geotechnical and Engineering Properties of Expansive Clayey Soil Stabilized with Biomass Ash and Nanomaterials for Its Application in Structural Road Layers. *Geomechanics for Energy and the Environment, 36*. doi:10.1016/j.gete.2023.100496

Elhassan, A. A., & Mnzool, M. (2023). Effect of clay mineral content on soil strength parameters. *Alexandria Engineering Journal*, 475-485.

Fatnanta, F. (2023). Permeability Prediction for Expansive Soil Based on Physical Properties Using Artificial Neural Networks. *Makara Journal of Technology, 27*, 51-57. doi:10.7454/mst.v27i2.1623

Federal Highway Administration. (2006). Geotechnical aspects of pavements (Publication No. FHWA NHI-05-037). National Highway Institute.

Federal Highway Administration. (2007). Long-Term Pavement Performance Project laboratory materials testing and handling guide: Protocol P60—Test method for determining expansive soils (SS12) (Publication No. FHWA-RD-07-052). U.S. Department of Transportation.

Hassan, W. (2023). Experimental Investigation of Mechanical Behavior of Geosynthetics in Different Soil Plasticity Indexes. *Transportation Geotechnics, 39*. doi:10.1016/j.trgeo.2023.100935.

Katte, V. Y. (2019). Correlation of California Bearing Ratio (CBR) Value with Soil Properties of Road Subgrade Soil. *Geotech Geol Eng, 37*, 217-234. doi:https://doi.org/10.1007/s10706-018-0604-x

Knappett, J. A., & Craig, R. F. (2012). *Craig's Soil Mechanics Eight Edition.* New York: Spon Press.

Li, X., and Zhang, Y. (2025). A coupled probabilistic site characterization method for estimating soil stratification and spatial variability using multiple-source site investigation data. *Engineering Geology, 351*, 108024. doi:10.1016/j.enggeo.2025.108024

Longley, P. G. (2015). *eographic Information Science and Systems (4th ed)*. Hoboken: NJ: john Wiley & Sons.

Ma, S., & Song, Y. (2023). Extended Wet Sieving Method for Determination of Complete Particle Size Distribution of General Soils. *Journal of Rock Mechanics and Geotechnical Engineering, 16*, 242-257. doi:10.1016/j.jrmge.2023.03.006

Mitchell, J. K., & Soga, K. (2005). *Fundamentals of Soil Behavior Third Edition.* New Jersey: John Wiley & Sons, Inc.

Morento-Maroto, J. M. (2021). Review and Critical Examination of Fine-grained Soil Classification Systems Based on Plasticity. *Applied Clay Science*, 105955. doi:10.1016/j.clay.2020.105955.

Officials, A. A. (2017). *AASHTO M145: Classification of Soils and Soil-Aggregate Mixture for Highway Construction Purposes.* American Assiciation of State highway and Transportation Officials.

Olayanju, G., & Mogaji, K. L. (2017). Foundation integrity assessment using integrated geophysical and geotechnical techniques: case study in crystalline basement complex, southwestern Nigeria. *Journal of Geophysics and Engineering, 14*(3), 675-690. doi:10.1088/1742-2140/aa64f7

Shi, Y., & Li, S. (2024). Compaction and Shear Performance of Lime-modified High Moisture Content Silty Clay. *Case Studies in Construction Materials, 21*. doi:10.1016/j.cscm.2024.e03529

Siswosoebrotho, B., & Widodo, P. (2005). The Influence of Fines Content and Plasticity On The Strength and Permeability of Aggregate for Base Course Material. *Proceedings of the Eastern Asia Society for Transportation Studies*, 845-856.

Sridharan, A., & Nagaraj, H. (2005). Hydraulic conductivity of remolded fine-grained soils versus index properties. *Geotechnical and Geological Engineering*, 43-60.

Xie, J., Huang, J., Lu, J., Burton, J., Zeng, C., & Wang, Y. (2022). Development of two-dimensional ground models by combining geotechnical and geophysical data. *Engineering Geology, 300*, 106579. doi:10.1016/j.enggeo.2022.106579