Laboratory Soil Classification and Analysis of Index Soil Properties of a Site in San Juan City, Philippines

Kevin C. Tan
De La Salle University

Patrick Matthew T. Chua
De La Salle University

Rongxuan Hou
De La Salle University

Joenel G. Galupino
De La Salle University

他

https://doi.org/10.5109/7395523

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 11, pp.232-238, 2025-10-30. International Exchange and Innovation Conference on Engineering & Sciences
バージョン：

Laboratory Soil Classification and Analysis of Index Soil Properties of a Site in San Juan City, Philippines

Kevin C. Tan[1], Patrick Matthew T. Chua[1], Rongxuan Hou[1], Joenel G. Galupino[1], Erica Elice S. Uy[1], Jomari Tan[1], Rainier Lawrence Valdez[1], Daniel Valerio[1]
[1]De La Salle University, Manila, Philippines,
Corresponding author email: kevin_c_tan@dlsu.edu.ph

Abstract: *This research examines the index soil characteristics of a construction area in San Juan City, a very urbanized and flood-prone city in Metro Manila. Soil samples from an excavation near Greenhills West Club House were subjected to laboratory analyses, such as specific gravity, Atterberg limits, Standard Proctor compaction, and grain-size distribution. The results yielded a specific gravity of 2.717, a plasticity index of 18.68%, and a distribution of approximately 20% Gravel, 65% Sand, and 15% Fines, indicating a medium plasticity. The soil was categorized as SC (Clayey Sand) according to the Unified Soil Classification System. An optimum moisture content of about 21.5% was determined, emphasizing the importance of moisture control in field compaction. The soil characteristics suggest moderate shear strength and low permeability, necessitating cautious consideration for construction purposes. These results present localized geotechnical information that aids safer and more efficient infrastructure planning in San Juan City.*

Keywords: Soil Classification; Geotechnical Engineering; San Juan City

1. INTRODUCTION

The success and stability of infrastructure projects are heavily dependent on their soil foundation [1]. Understanding soil behavior is significant for agriculture, environmental conservation, engineering, and construction [2]. Buildings can suffer issues, such as settling, instability, or failure, if soil properties are badly researched [3]. Soil studies are thus the foundation for sustainable and safe land development, especially in urban areas.

Analysis of index soil properties is a significant aspect of soil study [4]. Without requiring much testing, these properties provide general information regarding the composition and response of the soil. Engineers apply properties such as moisture content, plasticity, and particle size distribution to analyze the overall condition of the soil[5, 6, 7]. Professionals can make preliminary judgments regarding the behavior of the soil under various conditions by observing these properties[8].

Due to its urbanization factor and tendency to flood, San Juan City, which is a small but highly developed city in Metro Manila, has specific geotechnical concerns[9, 10]. Familiarity with the local soil conditions is important due to San Juan's increased demand for roads, drainage, and buildings[11]. The subject of the present study is an ongoing excavation beside the property of Greenhills West Club House, positioned just south of the Xavier School complex. Environmental resilience of the city will be improved, and safer infrastructure schemes will be addressed through a systematic analysis of the index properties of soil.

Index soil parameters such as particle size distribution, moisture content, specific gravity, and Atterberg limits (liquid and plastic limits) are some examples[12]. These properties provide information regarding the strength, compressibility, and permeability of the soil and are utilized to classify it. Even though index characteristics cannot directly evaluate strength, they are reliable indicators of how the soil will react to different loading conditions and environmental conditions[13].

Most engineering choices, ranging from selecting the proper foundation type to designing effective drainage systems, are based on an understanding of soil index values[14]. Highly plastic clays, for example, can expand or contract significantly, leading to structural cracks[15, 16]. At the same time, unstable foundations might be due to poorly graded sandy soils[17]. Therefore, engineers can design safer and less expensive structures by precisely determining the characteristics of the soil index.

Although general geotechnical information exists for Metro Manila, direct investigations of San Juan City soil conditions are lacking[18, 19, 20]. Because the nature of soil properties can differ radically within a small distance of kilometers, local examinations are needed [21]. Current site-specific information will prevent engineering design reliance on misleading ground condition assumptions within this urban setting.

This research will seek to identify the index soil properties of a chosen construction area in San Juan City using laboratory tests. The findings will present an in-depth soil classification and indicate major physical characteristics that affect construction and land development. Through providing a deeper insight into the local soil condition, this research expects to support improved, safer, and more sustainable infrastructure planning for San Juan City.

2. SITE DESCRIPTION AND SAMPLE COLLECTION

Soil samples were obtained from an active excavation site beside the Greenhills West Club House grounds immediately south of the Xavier School complex in San Juan City (14°36'01.7"N 121°02'31.4" E). A river lies next to the excavation area, although a wall lies between the site and the river. The surrounding area is fully urbanized, with only decorative vegetative cover. Sampling was conducted on 31 January 2025, under overcast skies following a light rainfall, which may have influenced near-surface moisture content. A Construction Shovel was used to extract samples at depths of 1m. A total of 4 Samples were collected in sacks weighing approximately 13-15kg each. Samples were stored in room temperature for 2 weeks until brought to storage in the laboratory.

3. METHODOLOGY

3.1 Specific Gravity Test

The specific gravity of the soil samples was determined in accordance with ASTM D854 [22]. A 500 mL volumetric flask was first filled with water to the calibration mark and weighed. Approximately half of the water was then removed, and the soil sample was introduced into the flask. The flask was immersed in boiling water and gently agitated to eliminate any entrapped air. After cooling, the flask was refilled to the calibration mark and weighed again. The water-soil mixture was transferred to an evaporating dish, weighed, and subsequently oven-dried to a constant weight. The final weight of the dry sample, along with the previous measurements, was used to calculate the specific gravity of the soil.

3.2 Atterberg Limits Test

The Atterberg Limits, comprising the liquid limit (LL) and plastic limit (PL), were determined following the procedures outlined in ASTM D4318 [23].

3.2.1 Liquid Limit

For the liquid limit, a soil paste was placed in the cup of the Casagrande device and leveled to approximately 10 mm depth. A standard grooving tool was used to create a groove in the soil, and the cup was repeatedly dropped until the groove closed. The number of blows required for closure was recorded, and a representative portion of the closed groove was taken to determine the moisture content. This process was repeated to acquire at least three data points to construct a flow curve, from which the liquid limit was obtained.

3.2.2 Plastic Limit

For the plastic limit, the same soil used in the liquid limit test was hand-rolled into threads until crumbling occurred at a diameter of approximately 3.2 mm. The crumbled material was collected, and multiple batches were processed until at least 6 grams of soil were obtained. The moisture content of the collected soil was determined to compute the plastic limit. Soils that failed to exhibit plastic behavior were classified as non-plastic (NP).

3.3 Standard Proctor Compaction Test

The compaction characteristics of the soil were assessed using the Standard Proctor Test, in accordance with ASTM D698 [24]. A compaction mold with known dimensions was assembled with an extension collar. Approximately 3 kg of soil, sieved to pass the No. 4 sieve, was prepared and mixed with water. The mixture was compacted in three layers, each receiving 25 blows from a standard rammer. After removing the collar, excess material was trimmed, and the mass of the mold with compacted soil was recorded. Moisture content samples were taken from the top and bottom layers. The remaining soil was rehydrated and compacted in subsequent trials to develop a compaction curve. The optimum moisture content (OMC) and maximum dry density (MDD) were identified from the curve.

3.4 Grain-Size Distribution Analysis

Grain-size distribution was determined using a combination of sieve analysis and hydrometer analysis, following ASTM D422 [25]. This combined approach was used to assess both the coarse and fine fractions of the soil samples.

3.4.1 Mechanical Sieve Analysis

For the sieve analysis, pre-weighed standard sieves were stacked in descending order of mesh size. A representative dry soil sample was placed in the top sieve and subjected to mechanical shaking for a fixed duration. The soil retained on each sieve was then weighed. The cumulative percent passing was computed and plotted against the corresponding sieve sizes to create a grain-size distribution curve for the coarse fraction (particles larger than 0.075 mm).

3.4.2 Hydrometer Analysis

For the hydrometer analysis, the soil fraction passing the No. 200 sieve was dispersed in a deflocculating solution, typically using sodium hexametaphosphate, and allowed to settle in a 1000 mL graduated cylinder. The suspension was thoroughly mixed using a mechanical stirrer to ensure uniform dispersion. A hydrometer was inserted into the suspension at specific time intervals (e.g., 0.5, 1, 2, 4, 8, 15, 30, 60, 120 minutes, etc.), and the corresponding readings were recorded. Temperature corrections and meniscus corrections were applied to the hydrometer readings. Using Stokes' Law and the recorded values, the effective particle diameters and the percentage of soil finer than each size were computed. These data were then combined with the sieve analysis results to produce a complete grain-size distribution curve.

3.5 Soil Classification (USCS)

Soil classification was performed according to ASTM D2487: Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) [26]. This classification integrated the results from the grain-size distribution and Atterberg limits tests. Soils were first categorized as coarse-grained or fine-grained based on the percentage passing the No. 200 sieve. Coarse-grained soils (more than 50% retained on the No. 200 sieve) were further classified based on the proportion of gravel and sand, while fine-grained soils (more than 50% passing the No. 200 sieve) were classified as clays or silts depending on their plasticity characteristics. Dual symbols were used where intermediate behavior was observed. The final classification was used to assess the engineering behavior and suitability of the soils at the excavation site in San Juan City.

4. RESULTS AND DISCUSSION

4.1 Specific Gravity Test

The specific gravity of the soil sample was determined to be 2.719 based on the test procedure following ASTM D854. After applying the temperature correction factor of 0.9991 for the measured water temperature of 24.4°C, the corrected specific gravity was calculated as 2.717. This value falls within the typical range for fine-grained soils, which generally ranges from 2.70 to 2.80 [27].

4.2 Atterberg Limits Test

The liquid limit of the soil was determined through the Casagrande method, using three trials with varying moisture contents and corresponding number of blows, the results are as shown below in Table 1.

Table 1. Liquid Limit Test

number of blows	Moisture Content(w)
17	38.59%
25	45.53%
32	43.60%

At 17 blows, the moisture content was 38.59%, indicating excess water; at 32 blows, the moisture content was 43.60%, indicating insufficient water. The Multipoint liquid limit plot is presented in fig. 1.

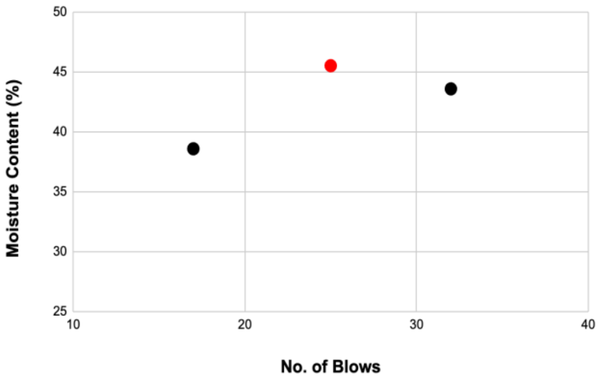

Fig.1. Multipoint liquid limit scatter plot

The optimal trial occurred at 25 blows, yielding a moisture content of 45.53%, which is taken as the liquid limit of the soil. This value falls within the typical range for silty or clayey soils and suggests intermediate plasticity [28]. The relatively high moisture content required for the soil to flow under the standard number of blows indicates a significant presence of fine particles, likely clays or silts. These characteristics imply that the soil can retain water and exhibit volume changes, which are critical considerations for construction and foundation design [29].

The plastic limit of the soil was determined by conducting three trials, each using 6 grams of moist soil and drying them in the oven, the results are as shown below in Table 2.

Table 2. Plastic Limit Test

No. of Trial	Moisture Content(w)
trial 1	27.12%
trial 2	27.12%
trial 3	26.32%

The Trials yielded an average plastic limit of 26.85%. This value reflects the water content at which the soil transitions from a plastic to a semi-solid state [30]. The consistency in results across the three trials indicates good test reliability.

When compared with the previously determined liquid limit of 45.53%, the calculated plasticity index is 18.68%, suggesting the soil exhibits medium plasticity. This plasticity range is typical of clayey silts or silty clays, which tend to retain moisture and may be prone to shrink-swell behavior—important factors in evaluating the soil's engineering performance, particularly for subgrade and foundation stability [31].

4.3 Standard Proctor Compaction Test

The Standard Proctor Compaction Test was conducted to determine the soil's optimum moisture content (OMC) and maximum dry density (MDD) following ASTM D698. Using a compaction mold that had a measured volume of 929.37 cm³ and a mass of 4.09 kg, Four compaction trials were performed with varying moisture contents and corresponding dry unit weights, The results are as shown below in Table 3.

Table 3. Standard Proctor Test

No. of trial	Average Moisture content	Net Mass of Compacted Specimen (Kg)	Dry Unit weight (N/m^3)
trial 1	19.39%	1.54	13600
trial 2	21.30%	1.64	14260
trial 3	24.33%	1.68	14250
trial 4	34.30%	1.65	12960

The moisture content ranged from 19.39% to 34.30%, while the dry unit weight varied between 13.60 kN/m³ and 14.26 kN/m³. The highest dry unit weight of 14.26 kN/m³ was achieved in Trial 2, which had an average moisture content of 21.48%, indicating that this point represents the maximum dry density and optimum moisture content of the soil. The Compaction Curve is presented in fig. 2.

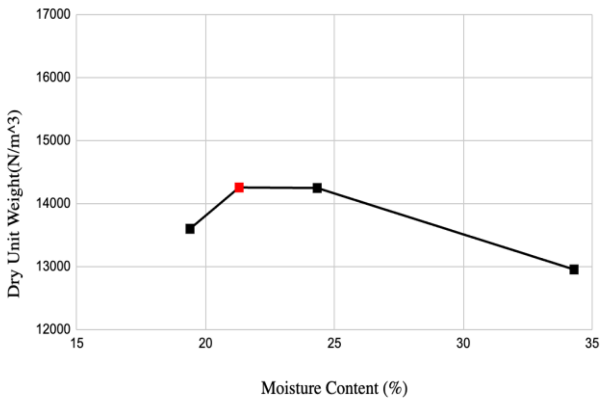

Fig. 2. Compaction Curve

These results suggest that the soil reaches its densest state when compacted at a moisture content of approximately 21.5%. The relatively moderate maximum dry density indicates the presence of a fine-grained soil, such as silty clay or clayey silt, which typically requires more water for optimal compaction. The trend in the results also follows the expected compaction curve behavior: dry density increases with moisture content up to the optimum point and then decreases beyond it due to excess pore water reducing interparticle contact [32, 33, 34, 35]. This data is essential for field compaction specifications, ensuring soil is compacted within ideal moisture conditions for structural stability and reduced settlement risk.

4.4 Grain-Size Distribution Analysis

4.4.1 Mechanical Sieve Analysis

The grain-size distribution of the soil sample was analyzed using mechanical sieving in accordance with ASTM D422. The Gradation Curve of the Mechanical Sieve Analysis is as presented in fig. 3.

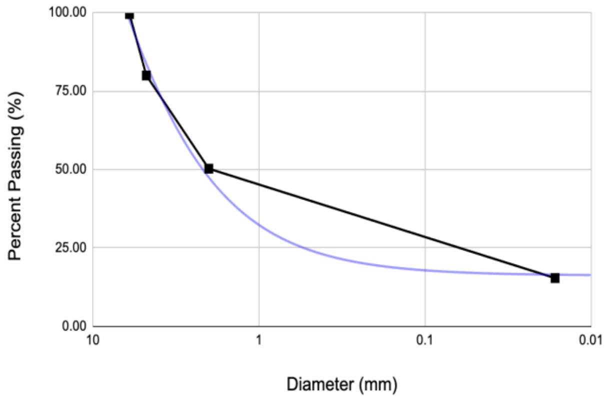

Fig. 3. Gradation Curve(Mechanical Sieve)

The mechanical sieve analysis, conducted in accordance with ASTM D422, revealed that 79.95% of the soil sample passed the 4.75 mm (#4) sieve, indicating that the soil is primarily composed of sand-sized particles. Further sieving showed that 50.26% passed through the 2 mm (#10) sieve and 15.41% through the 0.425 mm (#40) sieve. This distribution demonstrates that while the majority of the soil consists of coarse to medium sand, a significant portion of finer particles is also present. Only a small fraction of the soil falls below the #40 sieve, suggesting limited silt and clay content.

4.4.2 Hydrometer Analysis

The hydrometer analysis, performed to evaluate the fine fraction of the soil sample that passed the #200 sieve, provided insight into the percentage of silt and clay particles. Over a 24-hour sedimentation period, the hydrometer readings and corresponding effective particle diameters (D) revealed a progressive decrease in suspension density, reflecting the settling of finer particles over time. The Gradation Curve of the Hydrometer Analysis is as presented in fig. 4.

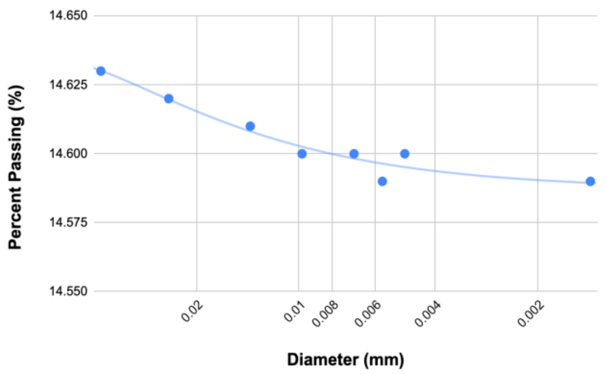

Fig. 4. Gradation Curve(Hydrometer)

At 2 minutes, the effective particle diameter was 0.0381 mm, indicating the presence of coarse silt particles, while at 1440 minutes (24 hours), the diameter dropped to 0.0014 mm, consistent with fine clay-sized particles. The corresponding percentage finer values (P) remained relatively stable around 14.59%, suggesting that only a small fraction of the soil consists of true fine-grained material.

The Final Gradation Curve Combining the Data Points from both Mechanical Sieve and Hydrometer Analysis is presented below in fig. 5.

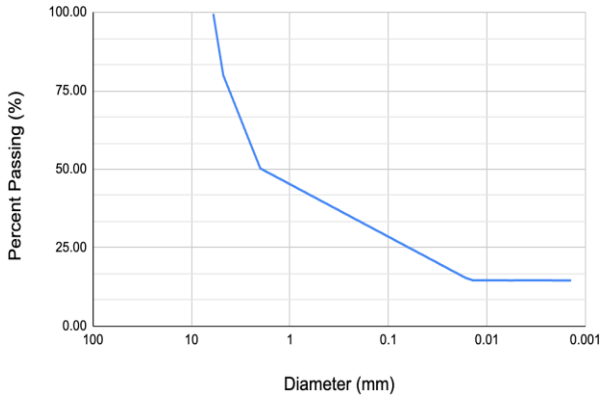

Fig. 5. Final Gradation Curve (Hydrometer + Mechanical Sieve)

4.5 Soil Classification (USCS)

Based on the laboratory test results, the soil sample from the San Juan City excavation site was classified using the Unified Soil Classification System (USCS) following ASTM D2487. A Flowchart of the Laboratory Soil Classification is presented in fig. 6.

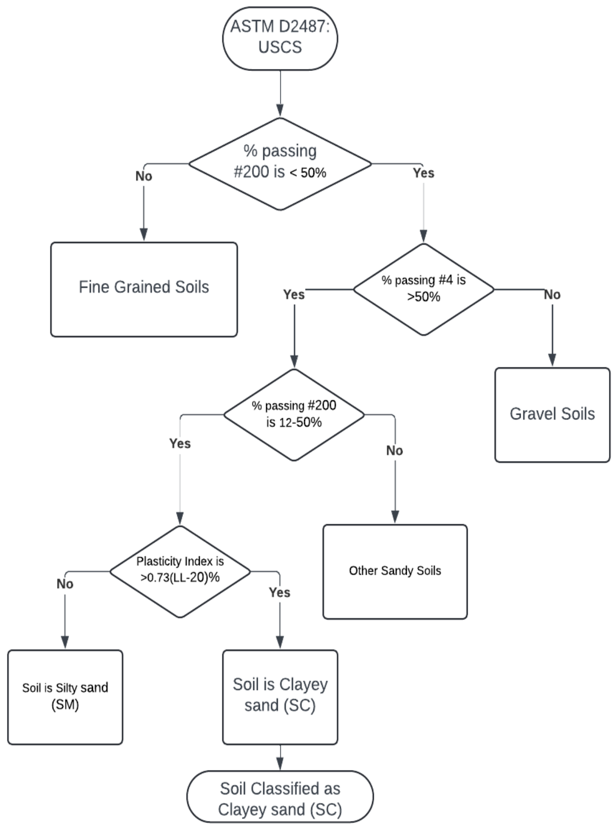

Fig. 6. Flowchart of the Laboratory Soil Classification

Based on the laboratory results, the soil sample exhibited a liquid limit (LL) of 45.53%, a plastic limit (PL) of 26.85%, and a plasticity index (PI) of 18.68%. Mechanical sieving showed that 79.95% of the soil passed the No. 4 sieve, indicating the soil is predominantly composed of sand-sized particles. Furthermore, approximately 14.6% passed the No. 200 sieve, confirming the presence of a significant amount of fine material. Since more than 12% of the sample is made up of fines, classification under the Unified Soil Classification System (USCS) relies on the plasticity characteristics of those fines.

When plotted on the Casagrande plasticity chart, the soil's plasticity index and liquid limit place it above the A-line, indicating clayey behavior of the fines. As a result, the soil is classified as SC (Clayey Sand) under USCS. This type of soil generally has good shear strength due to its sandy composition but may exhibit reduced permeability and increased plasticity because of the clay content[36, 37, 38]. Such characteristics are important for assessing the soil's suitability for foundation support and compaction behavior in geotechnical engineering applications [39].

4.6 Possible Applications for Newly Identified Soil

The soil sample was of clayey sand (SC) type, which, according to standard soil property tests, has good to fair compaction, slight to medium compressibility, and poor drainage [40]. These characteristics show that SC soils are fairly stable when compacted and can be used for general fill purposes. As a subgrade for pavement, they rate good to fair, indicating that they can function well under normal conditions but might need stabilization in high-traffic or high-moisture situations. In spite of this, SC soils are fair to poor base course materials because of their poor drainage and susceptibility to frost and should be avoided where freeze-thaw action or extended saturation is an issue. In the case of San Juan City, where flood control and drainage are most crucial, appropriate moisture management and potential treatment of the soils would be needed if SC soils are to be utilized in the foundation of infrastructures or on roadworks.

5. CONCLUSION

The index soil properties assessed in this study reveal that the excavation site in San Juan City predominantly consists of clayey sand (SC) with medium plasticity. The specific gravity, Atterberg limits, compaction characteristics, and particle size analyses collectively suggest that the soil exhibits sufficient shear strength due to its sandy content but may present compaction challenges and moisture sensitivity due to the presence of fines. The optimum moisture content of 21.5% and maximum dry density of 14.26 kN/m³ serve as valuable references for field compaction standards. These site-specific results address the gap in localized geotechnical data for San Juan and underscore the necessity of comprehensive soil analysis in urban development. Ultimately, the findings support safer, more reliable engineering decisions in designing foundations, drainage, and structural components in similar urban terrains.

6. RECOMMENDATIONS

Based on the findings of this study, two recommendations are proposed to enhance geotechnical practices and ensure safer construction in San Juan City, as listed below.

Further Strength Testing in order to supplement the index soil properties, it is recommended to conduct site-specific strength and consolidation tests, such as unconfined compression and Tri-axial tests. This will provide deeper insight into the soil's load-bearing behavior and long-term settlement characteristics [7, 41, 42, 43].

Moisture Management During Construction. The identified optimum moisture content of 21.5% highlights the need for moisture control during field compaction. Construction activities should be scheduled around weather conditions to avoid deviation from optimal compaction ranges, especially in a flood-prone area like San Juan.

On the basis of the present evaluation of soil conditions and the problems presented by slight to moderate compressibility, it is suggested that additional research be undertaken on the efficacy of different soil-strengthening additives, especially those that are cost-effective, environmentally friendly, and locally sourced. Promising examples of soil-strengthening additives have emerged, such as recycled products like recycled gypsum, industrial waste products, and new biopolymer-based stabilizers, since they have shown excellent results in strengthening the soil and minimizing settlement [44, 45, 46]. Comparative studies and field-scale trials must be considered to compare their performance, applicability, and compatibility with traditional geotechnical practices.

7. REFERENCES

[1] S. Geomechanics, Why is Soil Analysis So Important in Construction? SAALG GEOMECHANICS, https://www.saalg.com/post/why-is-soil-analysis-so-important-in-construction (accessed 30.04.25).

[2] The Royal Society, Soil Structure and Its Benefits, April 2020, Royal Society, London, 2020.

[3] A. Wahab, Z. Embong, M. Hasan, H. Musa, Q.U. Zaman, H. Ullah, Peat Soil Engineering and Mechanical Properties improvement under the effect of EKS Technique at Parit Kuari, Batu Pahat, Johor, West Malaysia, Bull. Geol. Soc. Malays. 70 (2020) 133–138. https://doi.org/10.7186/bgsm70202011.

[4] N.J.B. Dimalanta, N.V.R. Garcia, N.W. Lao, N.J. Galupino, N.M.A. Adajar, Investigation of the effects of waste stone powder as an additive for alluvial soil, Proc. Int. Exch. Innov. Conf. Eng. Sci. (IEICES) 10 (2024) 99–104. https://doi.org/10.5109/7323249.

[5] A.F. Elhakim, K. Elbaz, M.I. Amer, The use of light weight deflectometer for in situ evaluation of sand degree of compaction, HBRC J. 10 (2014) 298–307. https://doi.org/10.1016/j.hbrcj.2013.12.003.

[6] N. Panjaitan, Electrokinetic phenomena of cation exchange and its effect on the behaviour of expansive clays, Int. J. Geomate 13 (38) (2017). https://doi.org/10.21660/2017.38.74846.

[7]J.R. Dungca, J.G. Galupino, Artificial neural network permeability modeling of soil blended with fly ash, Int. J. GEOMATE 12 (2017) 76–83. https://doi.org/10.21660/2017.31.6549.

[8] E.E.S. Uy, M.A.Q. Adajar, J.R. Dungca, Assessment of critical-state shear strength properties of copper tailings, Int. J. Geomate 12 (32) (2017) 12–18.

[9] Geoadmin, City of San Juan, Metropolitan Manila 5 Year Flood Hazard Map, https://lipad-fmc.dream.upd.edu.ph/layers/geonode%3Aph137405000_fh5yr_10m#more (accessed 30.04.25). Published May 31, 2017.

[10] J. Castro, Strategic logistics planning for flood disaster prevention of economic zones in the Greater Manila Area, Philippines, Asia Life Sci. 24 (2) (2015) 823–840.

[11] D.J. Edelman, Managing the urban environment of Manila, Adv. Appl. Sociol. 06 (3) (2016) 101–133. https://doi.org/10.4236/aasoci.2016.63010.

[12] M. Hasan, M.S.I. Zaini, L.S. Yie, K.A. Masri, R.P. Jaya, M. Hyodo, M.J. Winter, Effect of optimum utilization of silica fume and eggshell ash to the engineering properties of expansive soil, J. Mater. Res. Technol. 14 (2021) 1401–1418. https://doi.org/10.1016/j.jmrt.2021.07.023.
[13] K. Chatterjee, D. Choudhury, Variations in shear wave velocity and soil site class in Kolkata city using regression and sensitivity analysis, Nat. Hazards 69 (3) (2013) 2057–2082. https://doi.org/10.1007/s11069-013-0795-7.
[14] R.I. Maduka, N.O. Ayogu, C.N. Ayogu, G.A. Gbakurun, Role of smectite-rich shales in frequent foundation failures in southeast Nigeria, J. Earth Syst. Sci. 125 (6) (2016) 1215–1233. https://doi.org/10.1007/s12040-016-0727-5.
[15] M. Sojoudi, B. Li, E. Norouzi, Finite element modeling of thermo-hydro-mechanical coupled processes in clay soils considering bound water dehydration, Acta Geotech. 19 (6) (2024) 3769–3784. https://doi.org/10.1007/s11440-024-02262-7.
[16] X. Wang, J. Li, X. Wang, Y. Zhang, D. Jiang, G. Zhao, Study on strength and microstructure of red clay reinforced by F1 ionic soil stabilizer, Appl. Sci. 12 (19) (2022) 9831. https://doi.org/10.3390/app12199831.
[17] K.A. Daud, Cohesionless soil properties improvement using bentonite, ARPN J. Eng. Appl. Sci. 13 (1) (2018) 271–275.
[18] C.E. Monjardin, A.B. Medina, Comparative analysis of Geotechnical and Geophysical Investigations for average shear wave velocity in Metro Manila, Energy Rep. 9 (2022) 38–47. https://doi.org/10.1016/j.egyr.2022.11.153.
[19] J.R. Dungca, I. Concepcion, M.C.M. Limyuen, T.O. See, M.R. Vicencio, Soil bearing capacity reference for Metro Manila, Philippines, Int. J. Geomate 12 (32) (2017) 5–11. https://doi.org/10.21660/2017.32.6556.
[20] A.S. Daag, O.P.C. Halasan, A.A.T. Magnaye, R.N. Grutas, R.U. Solidum, Empirical correlation between Standard Penetration Resistance (SPT-N) and Shear Wave Velocity (Vs) for soils in Metro Manila, Philippines, Appl. Sci. (Switzerland) 12 (16) (2022). https://doi.org/10.3390/app12168067.
[21] J. Galupino, J. Dungca, Estimating Ground Elevation using Borehole Information: A Case of Metro Manila, Philippines, Int. Exch. Innov. Conf. Eng. Sci. (IEICES) (2023) 25–30. https://doi.org/10.5109/5909058.
[22] M.E. Kalinski, Chapter 3: Measurement of Specific Gravity of Soil Solids, in: M.E. Kalinski (Ed.), Soil Mechanics: Lab Manual, 2nd ed., John Wiley & Sons, Chichester, UK, 2011, pp. 13–17.
[23] M.E. Kalinski, Chapter 4: Measurement of Liquid Limit and Plastic Limit, in: M.E. Kalinski (Ed.), Soil Mechanics: Lab Manual, 2nd ed., John Wiley & Sons, Chichester, UK, 2011, pp. 19–29.
[24] M.E. Kalinski, Chapter 8: Laboratory Soil Compaction, in: M.E. Kalinski (Ed.), Soil Mechanics: Lab Manual, 2nd ed., John Wiley & Sons, Chichester, UK, 2011, pp. 75–87.
[25] M.E. Kalinski, Chapter 5: Analysis of Grain Size Distribution, in: M.E. Kalinski (Ed.), Soil Mechanics: Lab Manual, 2nd ed., John Wiley & Sons, Chichester, UK, 2011, pp. 31–51.
[26] M.E. Kalinski, Chapter 6: Laboratory Classification of Soil, in: M.E. Kalinski (Ed.), Soil Mechanics: Lab Manual, 2nd ed., John Wiley & Sons, Chichester, UK, 2011, pp. 53–61.
[27] M.E. Kalinski, Section 3.6: Expected Results, in: Chapter 3: Measurement of Specific Gravity of Soil Solids, Soil Mechanics: Lab Manual, 2nd ed., M.E. Kalinski (Ed.), John Wiley & Sons, Chichester, UK, 2011, p. 15.
[28] University of the West of England, Soil classification, UWE Engineering. https://environment.uwe.ac.uk/geocal/soilmech/classification/soilclas.htm (accessed 30.04.25).
[29] J. Wagner, Mechanical properties of clays and clay minerals, in: Developments in Clay Science, 2013, pp. 347–381. https://doi.org/10.1016/b978-0-08-098258-8.00011-0.
[30] Global Gilson website: https://www.globalgilson.com/blog/atterberg-limits-a-quick-reference-guide (accessed 30.04.25).
[31] Z. Zhong, Q. Zhou, L. Lyu, P. Wu, T. Li, B. Yang, X. Fan, Time-dependent swell–shrink behavior of red-bed mudstone under cyclic wetting and drying, Bull. Eng. Geol. Environ. 82 (12) (2023). https://doi.org/10.1007/s10064-023-03496-7.
[32] R. Azoor, R.N. Deo, N. Birbilis, J. Kodikara, On the optimum soil moisture for underground corrosion in different soil types, Corros. Sci. 148 (2019) 1–13. https://doi.org/10.1016/j.corsci.2019.04.017.
[33] J. Wu, G. Yang, X. Wang, W. Li, PZT-based soil compactness measuring sheet using electromechanical impedance, J. Test. Eval. 48 (4) (2020) 2345–2357. https://doi.org/10.1520/JTE20200013.
[34] D. Sterpi, Effect of freeze–thaw cycles on the hydraulic conductivity of a compacted clayey silt and influence of the compaction energy, Appl. Clay Sci. 116 (2015) 1–8. https://doi.org/10.1016/j.clay.2015.02.011.
[35] E. Ganju, H. Kim, D. Tang, R. Salgado, Experimental investigation of matric suction in compacted fine-grained soils, Can. Geotech. J. 53 (11) (2016) 1783–1794. https://doi.org/10.1139/cgj-2016-0167.
[36] P. Palanisamy, P.S. Kumar, Effect of molarity in geopolymer earth brick reinforced with fibrous coir wastes using sandy soil and quarry dust as fine aggregate (Case study), Case Stud. Constr. Mater. 8 (2018) 347–358. https://doi.org/10.1016/j.cscm.2018.01.009.
[37] S. Nazari, M. Hassanlourad, E. Chavoshi, A. Mirzaii, Experimental investigation of unsaturated silt-sand soil permeability, Adv. Civ. Eng. 2018 (2018) 4946956. https://doi.org/10.1155/2018/4946956.
[38] I. Akinwumi, M. Onyeiwu, P. Epelle, V. Ajayi, Soil improvement using blends of coal ash and plantain peel ash as road pavement layer materials, Res. 12 (3) (2023) 41. https://doi.org/10.3390/resources12030041.
[39]E. Remy-Barraud, J. Mbarga, M. Lino, C. Daux, L. Vauloup, Alea foundation of the embankments of Lom Pangar, in: 26th Int. Congr. Large Dams, CRC Press/Balkema, 2018, pp. 382–402.
[40] G.F. Sowers, Introductory Soil Mechanics and Foundations, fourth ed., Macmillan, New York, 1979.
[41] W. L. Sing, R. Hashim, F. H. Ali, Behavior of stabilized peat soils in unconfined compression tests, American Journal of Engineering and Applied

Sciences, 1(4) (2008) 274–279. https://doi.org/10.3844/ajeassp.2008.274.279
[42] S. A. Naeini, B. Naderinia, E. Izadi, *Unconfined compressive strength of clayey soils stabilized with waterborne polymer*, KSCE Journal of Civil Engineering, 16(6) (2012) 943–949. https://doi.org/10.1007/s12205-012-1388-9
[43] Karumanchi, M., & Nerella, R. (2022). Shear strength parameters from digital tri-axial test and soils stabilization with extracted nanosilica. Nanotechnology for Environmental Engineering, 7(1), 307–318. https://doi.org/10.1007/s41204-022-00238-0
[44] An, Q., Pan, H., Zhao, Q., Du, S., Wang, D., "Strength development and microstructure of recycled gypsum–soda residue–GGBS based geopolymer," Constr. Build. Mater., 331 (2022) 127312. https://doi.org/10.1016/j.conbuildmat.2022.127312.
[45] Chen, C., Wu, L., Perdjon, M., Huang, X., Peng, Y., "The drying effect on xanthan gum biopolymer treated sandy soil shear strength," Constr. Build. Mater., 197 (2019) 271–279. https://doi.org/10.1016/j.conbuildmat.2018.11.120.
[46] Bhardwaj, A., Sharma, R.K., "Effect of industrial wastes and lime on strength characteristics of clayey soil," J. Eng. Des. Technol., 18 (6) (2020) 1749–1772. https://doi.org/10.1108/JEDT-12-2019-0350.