

A Novel Approach to the Classification of Soil Swelling Potential Using the Weighted Plasticity Index (wPI)

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Abstract

Expansive soils present a significant geohazard to light infrastructure worldwide, causing costly damage through swelling and shrinkage cycles driven by moisture content changes. One key property controlling this behavior, the Cation Exchange Capacity (CEC), is complex and expensive to measure directly, making it necessary to find reliable and affordable proxies for initial site assessments. This study introduces and validates a novel parameter, the weighted plasticity index (wPI), for classifying the swelling potential of expansive clays. Twenty-six soil samples, representing a range from low to high plasticity clays from Trinidad, underwent standard geotechnical laboratory tests, including Atterberg limits and grain size analysis. The wPI was calculated for each sample as the product of its Plasticity Index (PI) and the percentage of fine particles (percent passing the 425- μm sieve). A strong linear relationship ($R^2 = 0.94$) was found between the wPI and the Liquid Limit (LL). Using a previously established relationship between LL and CEC, a robust mathematical model connecting wPI directly to CEC was derived. This model formed the basis for a new four-tiered swelling potential classification system (Low, Medium, High, and Very High) based on the calculated wPI values. The wPI method provides a reliable, quick, and cost-effective tool for geotechnical engineers to evaluate swelling potential, promoting the design of more resilient and sustainable infrastructure in areas prone to expansive soils.

Keywords

Cation Exchange Capacity (CEC), Expansive Soils, Geotechnical Site Investigation, Swelling Potential, Weighted Plasticity Index (wPI)

1. Introduction

Soils that experience significant volume changes due to water content variations are called expansive soils (Alexander, Park, & Gay, 2020). These soils are common in tropical regions classified as arid or semi-arid and pose a substantial threat to civil infrastructure. The swelling of expansive soil during wet periods can cause unwanted heaving of shallow foundations, while drying periods can lead to damaging settlements. This cycle of movement results in costly damage to infrastructure, especially for roadworks and low-rise buildings (Jones & Jefferson, 2012). The proper classification and identification of expansive soil potential are essential early steps in any geotechnical design process to reduce these risks and guide suitable design choices.

The latest developments in geotechnical practice include several methods for soil classification, but many do not directly measure swelling potential. The two most common systems, the Unified Soil Classification System (ASTM D2487-17, 2017) and the AASHTO Soil Classification System (AASHTO, 2021), mainly describe soil texture and engineering properties for construction purposes but do not inherently identify a soil's tendency to expand. While both systems provide qualitative indicators (e.g., CH classification) they do not offer a quantitative rating of swelling potential, which this paper addresses. As a result, practitioners have traditionally relied on empirical correlations that connect a soil's swelling potential to more easily measurable index properties. Foundational research in this area has established links between expansivity and parameters such as the Liquid Limit (LL) and the Plasticity Index (PI) (Chen, 1988; Holtz & Gibbs, 1956). Further improvements led to the creation of a modified plasticity index, which includes the percentage of material passing a specific size, recognizing the significance of the fines fraction in controlling soil behavior (BRE, 1993).

The mechanism behind soil swelling mainly depends on the physicochemical and mineralogical makeup of the clay fraction (Mitchell & Soga, 2005; Mebarki et al., 2025). The presence of highly reactive clay minerals, especially montmorillonite, is a key factor in causing large volume changes (Holtz & Kovacs, 1981). The ability for volume change comes from water molecules with cations attaching to the surface of clay particles, which have a negative charge. A primary measure of this electrochemical property is the Cation Exchange Capacity (CEC), which indicates how many cations a clay particle can attract. There is a clear link between clay mineral types and CEC, with montmorillonite having a much higher CEC (60 - 150 meq/100 g) compared to less active minerals like kaolinite (3 - 15 meq/100 g) (Grim, 1968). As a result, CEC is a more essential indicator of swelling potential than basic index properties.

Despite its scientific importance, directly measuring CEC is time-consuming, requires specialized equipment and is often too expensive for routine geotechnical investigations. This has created a persistent gap between fundamental soil science and practical engineering use. A major breakthrough in closing this gap was achieved by Yilmaz (2004), who established a strong empirical link between the easily measured Liquid Limit and the more fundamental CEC shown in Equation

1. This work offered a practical way to estimate CEC from standard laboratory tests, resulting in a CEC-based classification system for swelling potential that builds upon earlier frameworks (Dakshanamurthy & Raman, 1973; Yilmaz, 2004).

$$CEC = e^{2.63+[0.02 \times LL]} \quad (1)$$

In Trinidad, expansive soils are a known geohazard, mainly found in the central and southern regions of the island (Venkataramana, 2002). These soils, formed from parent materials like clay shale and marl, are recognized for their high swelling potential. However, a quick, standardized, and cost-effective method for classifying this potential for local engineering use has not been well established, with assessments often relying on project-specific research. This underscores a crucial need for a practical tool that uses easily accessible soil data to reliably assess swelling risk. This paper aims to fill this research gap by accomplishing the following objectives:

- 1) To introduce and define a novel parameter, the weighted plasticity index (wPI), derived from standard geotechnical tests (Atterberg limits and grain size analysis).
- 2) To establish a strong empirical relationship between the wPI and basic soil swelling behavior by linking it to CEC through the established LL-CEC correlation.
- 3) To propose a new, practical wPI-based classification system for evaluating the swelling potential of Trinidadian soils, providing a cost-effective tool for preliminary site assessment.

2. Materials and Methodology

2.1. Site Description and Soil Sampling

The experimental program was conducted on twenty-six soil samples collected from various locations throughout Trinidad. The sampling sites were selected to ensure a broad spatial distribution and to capture a wide range of soil types, covering clays of low, medium, and high plasticity. At each location, undisturbed soil samples were retrieved from a depth of 1 meter using Shelby tubes. The samples were then transported to the University of the West Indies Soils Laboratory for extrusion and preparation for laboratory testing. The corresponding coordinates are provided in **Table 1** and the geographic locations of the sampling sites are shown in **Figure 1**.

Table 1. Locations of samples in the (UTM) coordinate system.

Soil Number	UTM Coordinates	
	Easting	Northings
1	679204.48 m E	1150005.41 m N
2	674072.66 m E	1150692.13 m N
3	701634.00 m E	1115987.00 m N
4	676085.28 m E	1149682.21 m N
5	671973.96 m E	1139214.90 m N

Continued

6	673348.61 m E	1135384.62 m N
7	675249.13 m E	1159571.94 m N
8	677415.00 m E	1175459.22 m N
9	677535.88 m E	1173386.20 m N
10	665531.14 m E	1128829.62 m N
11	675874.19 m E	1148947.74 m N
12	679419.26 m E	1146461.24 m N
13	667985.10 m E	1130047.45 m N
14	673526.00 m E	1181914.00 m N
15	674992.00 m E	1184133.00 m N
16	673795.00 m E	1183789.00 m N
17	670555.00 m E	1154110.00 m N
18	673109.00 m E	1184028.00 m N
19	674304.00 m E	1183466.00 m N
20	680570.00 m E	1126195.00 m N
21	693041.55 m E	1117936.65 m N
22	687805.00 m E	1119010.00 m N
23	689568.00 m E	1127849.00 m N
24	685365.00 m E	1124401.00 m N
25	675844.00 m E	1127124.00 m N
26	686225.00 m E	1126967.00 m N



Figure 1. Location of soil samples tested in the laboratory (Google Earth, 2020).

2.2. Laboratory Testing Program

Upon arrival at the laboratory, the soil samples were prepared for a series of standard geotechnical tests. The preparation procedure was similar to that used for the Atterberg limits test, involving oven-drying, pulverizing the soil clods, and sieving the material through a 425- μm (No. 40) sieve. A comprehensive laboratory testing program was then carried out to determine the index properties and engineering characteristics of each soil sample. The tests were performed according to ASTM International standards to ensure consistency and repeatability. The specific tests included Sieve Analysis (ASTM C136/C136M-19), Hydrometer Analysis (ASTM D7928-17), Atterberg Limits (ASTM D4318-17e1), Specific Gravity (ASTM D854-14), and Hydraulic Conductivity (ASTM D5856-15).

2.3. The Weighted Plasticity Index (wPI): A Novel Parameter

This study presents a new composite parameter, the weighted plasticity index (wPI), aimed at offering a more comprehensive measure of a soil's swelling potential than the Plasticity Index (PI) alone. The wPI is explicitly defined as the product of the PI and the percentage of fines (i.e., the material passing the 0.075 mm or No. 200 sieve), obtained from a combined sieve and hydrometer analysis.

The theoretical foundation for the wPI is that a soil's overall swelling behavior depends on both the mineralogical characteristics of its clay particles and the total amount of these particles. The PI acts as an indicator of the fines' quality, reflecting the type and activity of clay minerals; a higher PI typically indicates more expansive minerals like montmorillonite (Holtz & Kovacs, 1981). The percentage of fines indicates the amount of material (silt and clay) actively involved in soil-water interactions. By multiplying these two factors, the wPI creates a single index that combines both the quality and quantity of the fine-grained fraction, offering a more complete indicator of the soil's innate capacity for volume change.

3. Results and Analysis

3.1. Geotechnical Properties of Investigated Soils

The laboratory testing program yielded a comprehensive dataset characterizing the index properties and engineering classifications of the twenty-six soil samples. The results from the grain size analysis, Atterberg limits tests, and hydraulic conductivity measurements are summarized in **Table 2**. This table also includes the calculated value of the weighted plasticity index (wPI) for each sample, derived from the measured PI and percentage of fines. The soils were classified according to the Unified Soil Classification System (USCS) (ASTM D2487-17), revealing a range from lean clays (CL) and silts (ML) to fat clays (CH), as well as their expansive potential shown in **Table 3**.

Table 2. Soil samples Index properties.

Soil Number	PI	LL	PL	% No. 200 (%Fines)	% Silt	% Clay	Permeability K_s (m/s)	wPI
1	36	60	24	92.31	70.36	21.94	3.91E-08	33.14
2	22	44	22	85.43	58.99	26.45	6.94E-08	18.80
3	43	68	25	96.62	68.22	28.40	2.35E-08	41.47
4	36	61	25	95.33	49.51	45.82	2.66E-08	34.70
5	39	67	28	95.82	60.94	34.88	1.05E-08	37.18
6	49	81	32	97.52	90.78	6.74	1.04E-08	47.49
7	18	44	25	95.91	57.44	38.48	3.24E-08	17.65
8	10	40	29	87.90	66.84	21.06	9.55E-09	8.88
9	15	36	21	84.30	65.48	18.82	8.26E-09	12.48
10	40	90	50	99.66	50.94	48.72	2.67E-08	39.67
11	32	58	26	96.17	82.39	13.79	2.78E-09	30.67
12	41	66	25	98.22	85.23	12.99	3.33E-08	40.27
13	43	77	33	90.14	69.65	20.49	5.22E-08	38.76
14	2	20	18	34.33	29.09	5.24	6.79E-08	0.69
15	7	24	18	49.17	39.66	9.51	2.51E-09	3.30
16	4	33	29	73.78	54.03	19.76	2.67E-08	2.95
17	5	24	19	55.14	40.41	14.73	2.46E-09	2.76
18	2	14	12	14.80	12.23	2.57	4.93E-09	0.30
19	1	23	22	68.95	51.51	17.44	9.55E-09	0.36
20	43	74	31	98.65	53.35	45.30	4.28E-09	42.71
21	44	74	30	97.54	51.14	46.41	1.46E-08	42.56
22	44	76	31	94.63	49.66	44.97	4.21E-09	42.02
23	30	52	22	92.56	48.38	44.18	5.22E-08	27.69
24	52	83	31	92.93	48.57	44.36	6.06E-09	48.66
25	37	64	27	99.44	53.78	45.66	2.57E-09	36.86
26	34	61	27	94.78	49.04	45.74	3.4E-09	32.48

Table 3. Soil classification of laboratory samples

Soil Number	ASTM-D2487		Chen (1988) Expansive Potential	Seed et al. (1962) Expansive Potential
	Unified Soil Classification System (USCS)			
1	CH	Fat Clay	Very high	Very high
2	CL	Lean Clay	High	High
3	CH	Fat Clay	Very high	Very high
4	CH	Fat Clay	Very high	Very high
5	CH	Fat Clay	Very high	Very high
6	CH	Fat Clay	Very high	Very high
7	CL	Lean Clay	High	Medium
8	ML	Lean Clay	Medium	Medium
9	CL	Silt	High	Medium

Continued

10	CH	Fat Clay	Very high	Very high
11	CH	Fat Clay	High	High
12	CH	Fat Clay	Very high	Very high
13	CH	Sandy Fat Clay	Very high	Very high
14	ML	Sandy silty clay	Low	Low
15	CL-ML	Silt with Sand	Medium	Low
16	ML	Sandy silty clay	Low	Low
17	CL-ML	Gravelly silty clay with sand	Low	Low
18	ML	Gravelly silty with sand	Low	Low
19	ML	Gravelly silt	Low	Low
20	CH	Fat Clay	Very high	Very high
21	CH	Fat Clay	Very high	Very high
22	CH	Fat Clay	Very high	Very high
23	CH	Fat Clay	High	High
24	CH	Fat Clay	Very high	Very high
25	CH	Fat Clay	Very high	Very high

3.2. Correlation between wPI and Liquid Limit

A linear regression analysis was conducted to examine the relationship between the calculated wPI and the measured Liquid Limit (LL) for the twenty-six soil samples. The analysis showed a very strong positive correlation between the two parameters, as shown in **Figure 2**. The relationship is described by the following linear Equation 2.

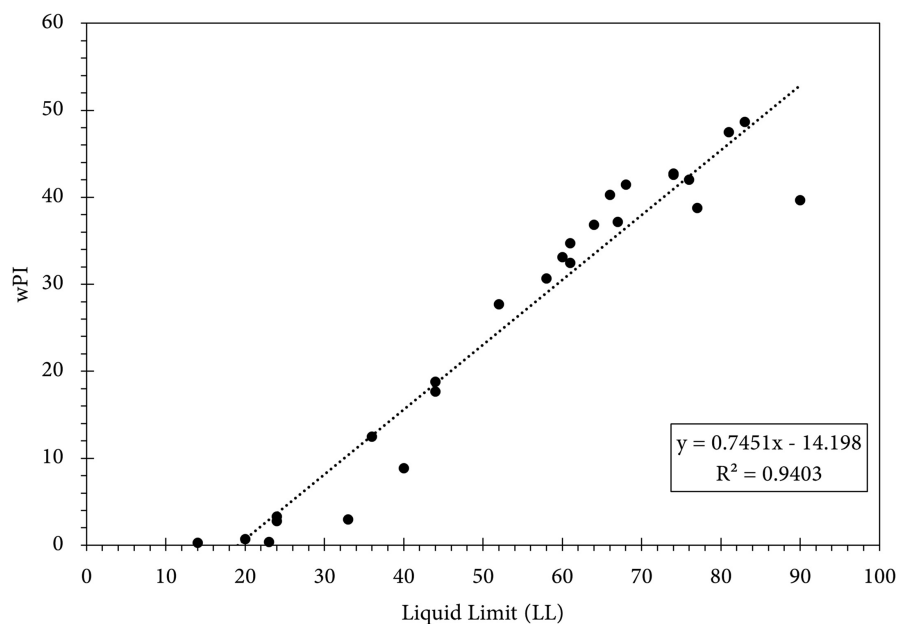


Figure 2. Correlating the parameters wPI and LL

$$wPI = 0.7451 \times (LL) - 14.198 \quad (2)$$

The coefficient of determination (R^2) for this regression was found to be 0.94, indicating that 94% of the variance in the wPI can be predicted from the LL. This high R^2 value signifies a strong and dependable linear relationship between the two parameters for the soils investigated.

3.3. Derivation of the wPI-CEC Relationship

To relate the empirical wPI parameter to the more fundamental soil property of Cation Exchange Capacity (CEC), a two-step approach was taken, utilizing the strong exponential relationship established by Yilmaz (2004) between CEC and Liquid Limit (LL). The correlation established by Yilmaz (2004) is based on 139 fine-grained alluvial soil samples sourced from various locations across Türkiye, providing a generalized foundation for the LL-CEC relationship. These alluvial soils are characterized by a mixed mineralogy, with dominant clay fractions consisting of expansive smectite and non-expansive kaolinite, alongside lesser amounts of illite and chlorite. This mineral blend provides the justification for the wide range of swelling behavior and physicochemical properties studied. The highly successful exponential relationship derived from these data is given previously in Equation (1), which showed a very strong fit with a correlation coefficient R^2 of 0.97 (Yilmaz, 2004). Applying this correlation to Trinidadian soils is strengthened by knowing the Turkish dataset represents a diverse, mixed-mineralogy alluvial origin.

A new equation linking CEC directly to wPI was derived through a two-step mathematical substitution. First, the empirical relationship between LL and wPI given in Equation (2) was rearranged to express LL as a function of wPI.

$$LL = (wPI + 14.198) / 0.7451 \quad (3)$$

Next, this expression for LL (Equation 3) was substituted into Equation (1). This substitution yields Equation 4, a direct relationship between CEC and wPI:

$$CEC = e^{2.63 + [0.02 \times ((wPI + 14.198) / 0.7451)]} \quad (4)$$

Simplifying the exponent gives:

$$CEC = e^{3.011 + (0.0268 \times wPI)}$$

Which can be expressed in the final form:

$$CEC = 20.31 \times e^{0.0268 \times wPI}$$

This derived equation provides a novel method to estimate the Cation Exchange Capacity of a soil directly from its calculated weighted plasticity index. Additionally, we can solve for wPI with respect to CEC, giving Equation 5.

$$wPI = (37.31 \times \ln(CEC)) - 112.35 \quad (5)$$

3.4. A New Swelling Potential Classification Based on wPI

Using the derived relationship between CEC and wPI (Equation 4), a new swelling

potential classification system was developed. The CEC threshold values for Low, Medium, High, and Very High swelling potential, as defined by Yilmaz (2004), were used as the benchmark. The corresponding wPI values for each threshold were calculated using Equation (5). The resulting classification system, which allows for the direct assessment of swelling potential using the wPI, is presented in Table 4 and shown in Figure 3.

Table 4. Swelling Classification based on the Weighted Plasticity Index.

Swelling Classification	Swelling Classification Parameters	
	Cation exchange capacity meq/100g	Weighted Plasticity Index (wPI)
Low	<27	<10.6
Medium	27 - 37	10.6 - 22.3
High	37 - 55	22.3 - 37.1
Very High	>55	>37.1

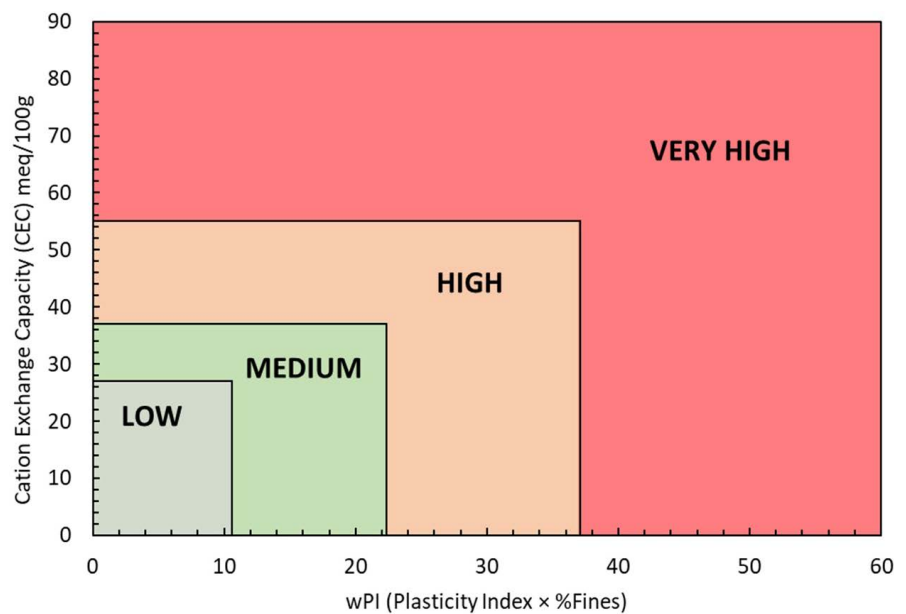


Figure 3. New soil swelling classification based on the weighted plasticity index (wPI) and the cation-exchange capacity (CEC).

4. Discussion

4.1. The Robustness of the wPI as a Predictive Tool

The results show that the weighted plasticity index (wPI) is a highly effective parameter for characterizing the swelling potential of fine-grained soils. The strong coefficient of determination ($R^2 = 0.94$) in the linear relationship between wPI and Liquid Limit (LL) provides solid empirical support for the new parameter. This means that the wPI is not just an arbitrary index but a dependable indicator of the key soil properties that influence water retention and plasticity. The strength of this correlation can be linked to the composite nature of the wPI itself. Unlike

classifications that depend only on PI or LL, the wPI combines both the quality of clay minerals (shown by PI) and the amount of fine particles (indicated by % fines). This dual approach offers a more comprehensive physical basis for evaluating a soil's overall ability to interact with water and change volume, which likely explains its strong predictive ability.

Furthermore, the usefulness of the wPI goes beyond predicting swelling potential; it also applies to unsaturated soil mechanics. Estimating the Soil-Water Characteristic Curve (SWCC), which is key for understanding unsaturated soil behavior, can be simplified using soil index properties. Researchers have successfully developed methods to estimate the SWCC from properties like grain-size distribution and the plasticity index, showing how a soil's physical traits relate to its water retention abilities (Perera, Zapata, Houston, & Houston, 2005; Chai & Khaimook, 2020). This method is especially useful because direct measurement of the SWCC is time-consuming and costly. Foundational studies have demonstrated that basic soil properties can reliably predict unsaturated soil behavior, opening the door for more practical applications in routine engineering (Zapata, 1999). Providing a dependable proxy, the wPI can greatly improve efficiency in critical tasks like forensic investigations of landslides, where rainfall-driven changes in suction are a main trigger (Rahardjo, Satyanaga, & Leong, 2019). Using a strong index parameter like the wPI, which combines both plasticity (PI) and fines content (% fines) into a single metric, provides a more robust input for empirical Soil-Water Characteristic Curve (SWCC) models than using either parameter alone. Estimating the SWCC this way allows for faster and more affordable modeling of slope stability under different moisture conditions (Alexander, Park, & Gay, 2020).

4.2. Comparison with Existing Classification Systems

When applying the proposed wPI classification system to the 26 soil samples and comparing it with established methods, its usefulness becomes clearer. For example, many soils labeled as "Very High" potential by Chen (1988) are similarly classified by the new wPI method (e.g., soils 1, 3, 4, 5, 6, 10). This alignment with past frameworks builds confidence in the new system. However, the wPI method also offers a more detailed evaluation in some cases. Take Soil #7 (PI = 18, %Fines = 95.97%), which is rated as "High" potential by Chen (1988) but "Medium" by Seed et al. (1962). The wPI for this soil is 17.65, placing it in the "Medium" swelling potential category under the proposed system. This indicates that although the soil's plasticity is relatively high, the overall amount or nature of its fines may reduce its swelling capacity, illustrating the benefit of the composite index over methods based solely on plasticity. By linking mathematically to the fundamental parameter of CEC, the wPI classification can offer a more scientifically based assessment than methods relying solely on PI, potentially avoiding over-conservative estimates in some cases and correctly identifying risks in others.

4.3. Practical Implications for Geotechnical Engineering

The main contribution of this research is its practical application. Determining CEC is a specialized and costly lab process, often outside the scope of initial geotechnical studies, especially for smaller projects or in developing regions. The wPI method offers a scientifically supported yet affordable alternative. The parameters needed to calculate wPI Plasticity Index and percent of fines come from two of the most common and inexpensive tests in geotechnical engineering: Atterberg limits and sieve analysis. This enables engineers to quickly evaluate the swelling potential of soils using readily available data, saving time and money during the crucial site investigation stage.

This practical advantage has direct implications for environmental protection and sustainable development. Early and accurate identification of expansive soil hazards allows for better land-use planning and the implementation of suitable engineering solutions from the beginning. This proactive approach helps prevent premature infrastructure failure, thereby reducing significant material waste, resource use, and the carbon footprint linked to costly repairs and rebuilds. By enabling the design of more resilient and durable structures, the wPI method supports more sustainable construction practices on challenging soils.

4.4. Limitations and Future Research

While the proposed methodology offers a significant practical advance, its limitations must be acknowledged to guide future research. The main limitation of this study is that the correlation between wPI and CEC is established indirectly. The derivation depends on the LL-CEC relationship developed by [Yilmaz \(2004\)](#) from a different soil dataset. The current study did not include direct laboratory measurements of CEC on the 26 Trinidadian soil samples to validate the final derived equation (Equation 4). Therefore, although the framework is logical and the initial wPI-LL correlation is strong, the final wPI-CEC relationship remains an estimate that needs direct verification. This limitation clearly defines a path for future research. The most important next step is to perform direct CEC testing on the Trinidadian soils analyzed in this study or on a similar representative set. This would enable a direct correlation between wPI and measured CEC, which could confirm or refine the proposed classification thresholds. Further research could also expand the soil database to include a wider range of parent materials and geological formations to test the global applicability of the wPI-CEC relationship.

5. Conclusion

This study addresses the critical need for a quick and affordable method to assess the swelling potential of expansive soils. A novel parameter, the weighted plasticity index (wPI), was developed, defined as the product of the Plasticity Index and the percentage of fines. Based on extensive laboratory testing on 26 soil samples from Trinidad, it is important to note that the specific wPI threshold values and the resulting classification system are calibrated for these Trinidadian soils. Ap-

plication of this system in other geological regions may require local validation to ensure accuracy. The main contributions and findings are as follows:

- A strong linear relationship ($R^2 = 0.94$) was found between the wPI and the Liquid Limit, confirming that the wPI is a reliable indicator of soil behavior.
- Using an existing link between Liquid Limit and Cation Exchange Capacity (CEC), a new mathematical model, was developed to estimate the core swelling property (CEC) from the easily calculated wPI.
- A practical, four-tiered swelling potential classification system (Low, Medium, High, Very High) based on wPI thresholds was introduced, offering a straightforward tool for engineering evaluation.

The wPI method provides a fast, affordable, and practical tool for engineers and geoscientists. It can significantly enhance initial site investigations, resulting in improved foundation and pavement designs, and supporting the development of safer, more sustainable, and resilient infrastructure on expansive soils. Future research should aim to directly measure CEC in the lab to validate and potentially refine the proposed wPI-based classification system.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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