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Research paper

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Geotechnical identification of soil deposits and clay sensitivity evaluation: A case study from East Algeria

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Summary

This article provides an overview of a comprehensive study conducted in the Tebessa region of Algeria to identify and characterize sensitive soils susceptible to swelling. This phenomenon poses significant challenges to construction activities and infrastructure development in the area. The study employed a multidisciplinary approach, combining geotechnical and mineralogical analyses to understand the behavior of sensitive soils in the region.

Geotechnical investigations involved laboratory identification tests, including Atterberg limits, grain size analysis, methylene blue value, sedimentometry, as well as mechanical tests: oedometer swelling and compressibility tests. Additionally, over 110 boreholes in four sectors were drilled in order to collect soil samples for the analysis.

Classification of the studied soils was performed based on grain size distribution, Atterberg limits, and geotechnical properties, utilizing classification systems like LPC and GTR. Results indicated that the sensitive soils in the Tebessa region predominantly belonged to highly plastic clayey categories, exhibiting medium to extremely high swelling potential.

Mineralogical analysis through X-ray diffraction provided insights into the composition of the clay fraction, with a focus on identifying swelling clay minerals, such as smectites. The study identified a significant presence of smectites in the soil samples, which are known for their high swelling potential.

Integrating geotechnical and mineralogical analyses allows engineers to correlate mineral compositions with soil behaviors such as compaction, consolidation, and shear strength. This correlation predicts how the soil will respond to engineering activities such as construction and slope stability. In the Tebessa region, this integration improves the understanding of clayey soil behavior, aiding informed decisions for sustainable development and resilient infrastructure.

Keywords

Tebessa region • sensitive soils • geotechnical analysis • mineralogical analysis • soil classification

1. Introduction

The Tebessa region in north-eastern Algeria is undergoing rapid urbanization, driven by an increasing demand for construction. However, this development faces significant challenges due to problems related to sensitive soil behavior, particularly soil swelling in areas with clayey soils. Soil swelling can cause significant structural distress and infrastructure damage, which calls for a comprehensive understanding of soil behavior [Hamed et al. 2023, Nelson et al. 1997].

In the Tebessa region, various degrees of damage have been observed on roads, low-rise buildings, and a portion of the airport runway. Damage ranges from simple cracking of walls and sidewalks to severely broken structures. Cracking tends to be diagonal on walls, often passing through window corners (Fig. 1) [Berrah et al. 2018]. Sidewalks have extensive cracking and uneven surfaces, particularly near residential areas. The issue is exacerbated by the expansion of housing and road construction. Consequently, the Public Works Department requires that swelling pressure and percentage are systematically considered in construction projects.

Source: Berrah et al. [2018]

Fig. 1. Damage to buildings caused by expansive soils in the first year after completion of the structure

Therefore, this study aims to conduct a geotechnical and mineralogical analysis in the Tebessa region and to estimate the soil swelling potential by quantifying the percentage of these minerals in the soil. The dry unit weight, the plasticity index, the degree of saturation and the preconsolidation pressure also have the greatest effect on the swelling pressure of the clayey soil in the Tebessa region [Berrah et al. 2020].

Firstly, the study determines the pressure exerted by clayey soil using laboratory identification tests (Atterberg limits, grain size analysis, methylene blue value, and sedimentometry) and mechanical tests such as oedometer swelling and compressibility tests.

Identification of swelling clays is achieved through mineralogical analysis using X-ray diffraction analysis. Most direct methods for determining swelling pressure are carried out by laboratory oedometer tests [Holtz et al. 1956, Lambe 1960], although some authors have conducted field tests [Ofer et al. 1985].

2. Materials and methods

2.1. General settings

The Tebessa region, located in northeastern Algeria, encompasses diverse geological and environmental settings that influence sensitive soil behavior and land use patterns. Situated at the intersection of the Mediterranean and Saharan climates, the study area has an arid/semiarid Mediterranean climate [Mihi et al. 2022]. It experiences significant climate variations, with hot, dry summers and mild, wet winters. These climatic conditions, coupled with the region's geological features, shape the distribution and properties of sensitive soil, with clayey soils being prevalent in many areas [Ibtissam et al. 2023].

The topography of the Tebessa region is characterized by a mixture of plains, plateaus, and low mountain ranges, including the Aurès Mountains to the south and the Tell Atlas to the north [Taib et al. 2022]. These landforms contribute to variations in soil erosion, drainage patterns, and sediment deposition, influencing the stability and resilience of the overall landscape to environmental change [Tamani et al. 2019].

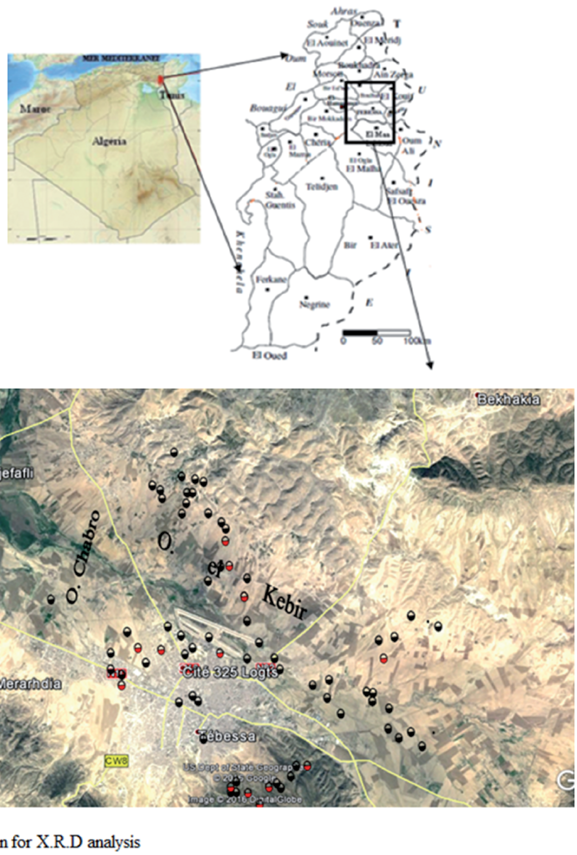
The geology of the Tebessa region is characterized by diverse rock formations, including sedimentary, metamorphic, and igneous rocks, which were exposed to extensive weathering and erosion processes over time [Hamad et al. 2021]. The geological nature of the most of the formations in the study area comprises marly clays and gypsum-bearing grayish-green marls with low compactness. The presence of clayey tuffs, limestones, and sandy tuffs has been recorded in certain boreholes. This geological diversity gives rise to a wide range of soil types, each with its unique composition, texture, and mechanical properties. Clayey soils, formed by the weathering of clay-rich parent materials, are particularly common in areas with low relief and moderate drainage [Bencharef et al. 2022].

The Tebessa region exhibits a complex interaction of geological, climatic, and environmental factors that shape soil behavior and land use dynamics. Understanding these general settings is essential for conducting comprehensive studies on soil properties, land management strategies, and sustainable development initiatives in the region [Hamed 2022].

2.2. Sampling and analysis

Soil investigations are performed by core drilling within the study area. Over 110 boreholes, ranging in depth from 2 to 20 meters, were used, and additional samples were collected from excavations and trenches. The necessary data obtained cover an area of approximately 100 km² across four sectors (El-Kouif Road, El-Merdja, Constantine Road, and the city center) (Fig. 2), where clay and marl layers can reach a thickness of up to 200 meters according to geological studies [Durozoy 1948, Bles et al. 1970].

For mineralogical identification, 14 samples taken from the most damaged soils (Fig. 2) were analyzed at the Clays and Paleoclimates Laboratory of the University of Liège in Belgium using the Bruker D8-Advance type X-ray diffractometer. Other complementary analyses, directly linked to the mineralogical analysis, can contribute enormously to the use of the swelling potential of clays. These analyses cover specific shape and surface area, water adsorption and swelling capacity, cation exchange capacity.



Source: Authors' own study

Fig. 2. Location of boreholes in the study area

2.3. Methods

The physical and mechanical properties of the 110 samples taken from the studied sites are determined by the following geotechnical analyses: particle size distribution by sieving and hydrometer test, Atterberg limits (liquid limit and plasticity index), natural water content, the dry density, methylene blue value, and swelling pressure under the oedometer test.

The soil classification is based on classification systems like USCS (Unified soil classification system), LPC (bridges and roads laboratory) and GTR (road earthworks guide) that provide detailed descriptions of clayey soils. For instance, in the LPC classification, clayey soils correspond to fine soil classes with over 50% of particles smaller than 80μm and containing organic matter (OM). The GTR classification, according to NF P 11-300 standard, commonly used for earthworks and embankments, characterizes soil based on grain size distribution, water sensitivity, and natural moisture content.

In mineralogical analysis, the clay mineral identification process is based on the analysis of diffractograms to identify clay minerals and determine their percentage in the soil sample, with particular attention paid to the fine fraction. The process involves two main steps:

Bulk test

The soil sample is sieved to isolate the fraction smaller than 250 microns. A diffractogram is carried out to identify the clay minerals present. In our case, these are essentially calcite, gypsum, clays and quartz. Corrections are applied to determine the percentage of total clay in each sample (Fig. 3).

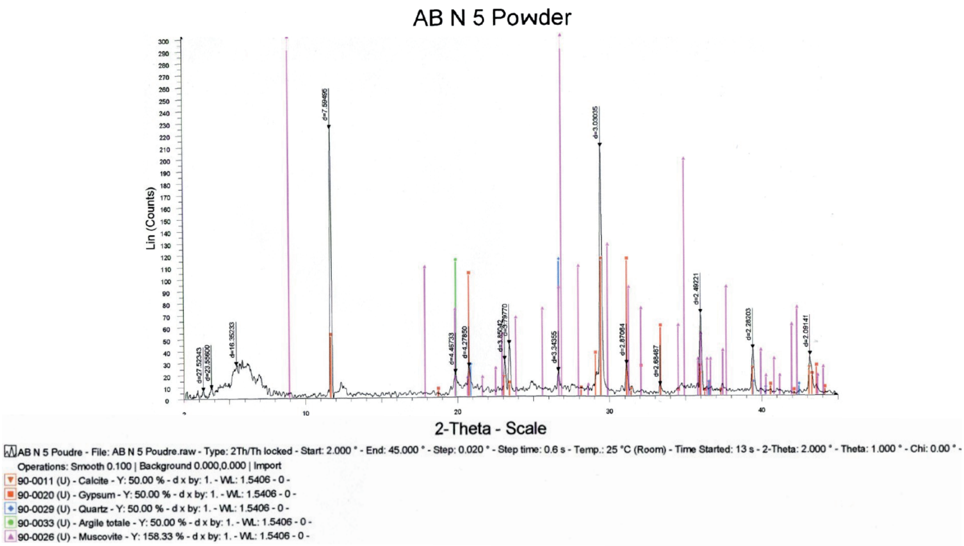


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Fig. 3. Diffractogram of a sample taken from the study area (bulk analysis)

Test on the fine fraction

The fraction smaller then 2 microns is processed to remove impurities, then subjected to diffractogram analyses after saturation with ethylene glycol and drying. Three spectra of minerals in their natural state, glycolated, and after heating, help identify the different types of clay minerals present (Fig. 4).

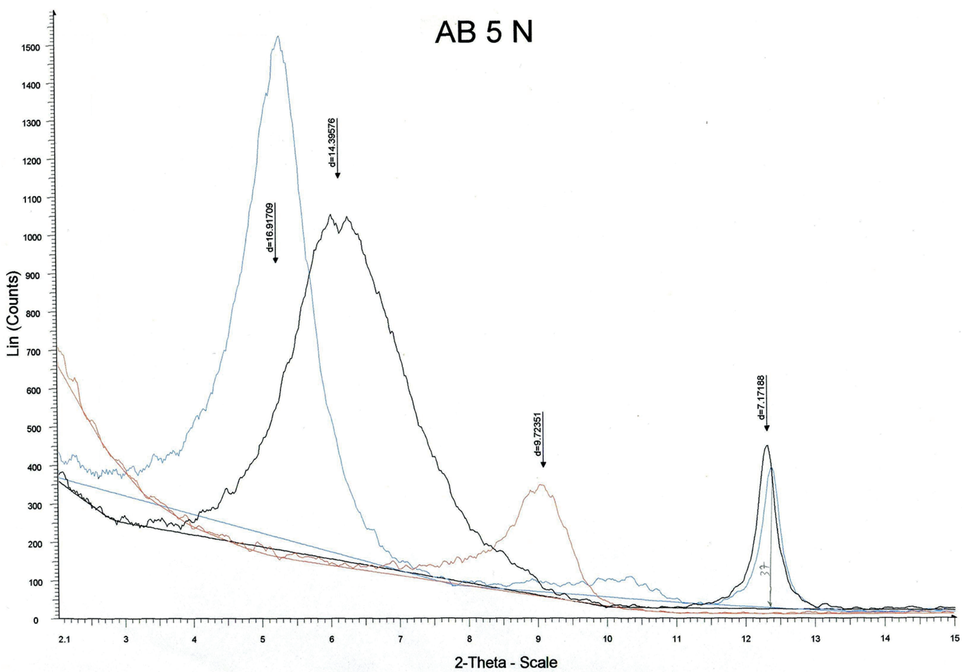

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Fig. 4. Diffractogram of a sample taken from the study area

Interpreting X-ray diffraction spectra involves several key steps: identifying background noise, locating diffraction peaks, assigning d-values, noting peak shifts for mineral identification, measuring peak intensity, and estimating mineral abundance by considering peak shape and technical factors.

3. Results and discussion

3.1. Grain size distribution of studied soils

Grain size analysis classifies soils as coarse or fine based on particle size. Soils with > 50% particles > 0.08mm are coarse, < 50% are fine, further classified by plastic behavior. LPC and GTR classifications were used in this study.

The LPC classification, based on the USCS, employs grain size analysis for coarse matrix soils and Atterberg limits for fine matrix soils. In the case of Tebessa clay, it falls into the categories of highly plastic clays (CH) and moderately plastic clays (Ap). (Fig. 5).

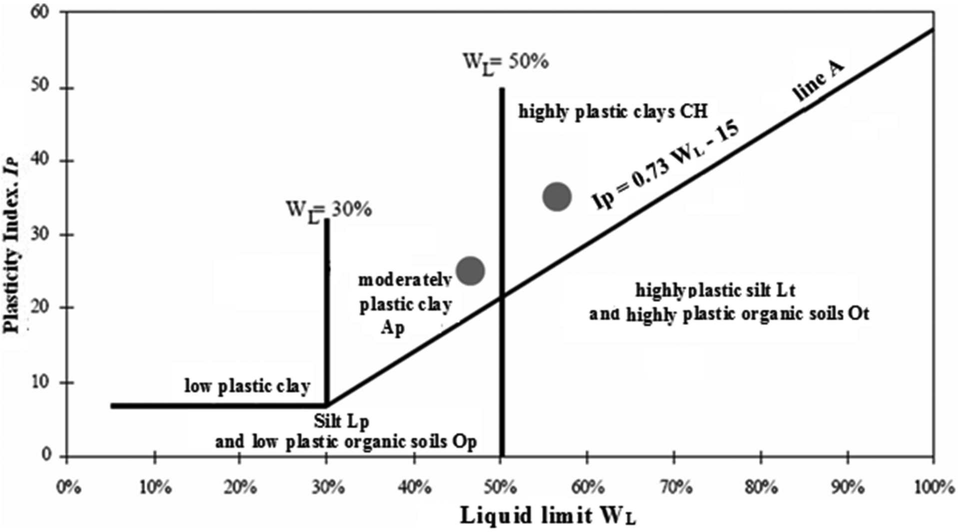

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Fig. 5. LPC classification of fine soils: Tebessa clay representation

According to the GTR classification, Tebessa clay falls under the A3 class, representing clayey and marly clays, very plastic silts, and the A4, representing highly plastic clayey and marly soils. This is in line with the LPC classification and even the visual description of the core samples.

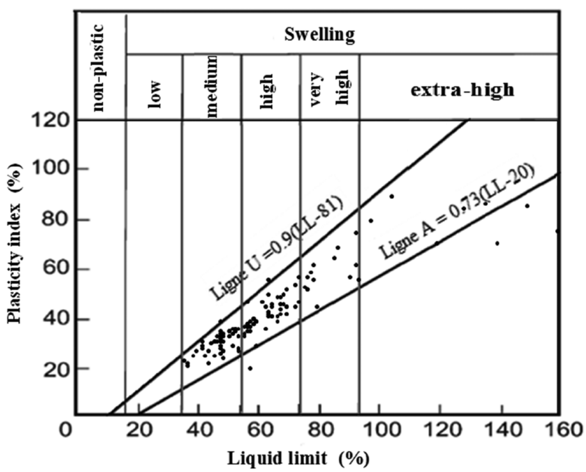
3.2. Atterberg limits

The liquid limit (Wl) and the plasticity index (Ip) not only allow to determine the plasticity of soils, but also provide insight into their swelling potential using the Casagrande chart [Badenhorst 2017, Soltani 2018]. The consistency limits, liquid limits (WI) and plasticity limits (PL), not only serves as the basic means of soil classification, but have also been shown to provide estimates of strength and deformation parameters via empirical correlations [Wroth and Wood 1978, Bobei 2013].

Analysis of the test results from the studied soils (Table 1) indicates soils with medium to high plasticity, according to the Casagrande chart. The Dakshanamurphy and Raman classification (Fig. 6) further classifies these soils as having medium to extremely high swelling potential for some samples, confirming the severity of the swelling phenomenon in certain areas within the study region.

Table 1. Summary of geotechnical characteristics of soils in the study area

Symbol	Description	Values/Classification
γd (kN · m^{-3})	Dry unit weight	11.6–2.06 (kN · m^{-3})
W (%)	Initial water content	8–38.24 (%)
F_f (%) < 80 µm	Soil fraction < 0.08 mm	44–98.18 (%)
Fc (%) < 0.02	Soil fraction < 0.02 µm (%)	26.29–56.16 (%)
W_l (%)	Liquid limit	36–160 (%)
I_P (%)	Plasticity index (%)	19–85 (%)
A	Activity (Ip / < fraction 0.02 µm)	0.4–2.13
VBS (g/100 g of dry soil)	Methylene blue value	2.2–10.84 (g/100 g of dry soil)
Cc	Compression index	0.123–0.534
Cs	Swelling index	0.01–0.84
Pc (kPa)	Preconsolidation pressure	37.5–270 (kPa)
Ps (kPa)	Swelling pressure	60–670 (kPa)
$CaCo_3$ (%)	Calcium carbonate percentage	68.1–1.53 (%)
Gypsum (%)	Gypsum percentage	60.86–1.51 (%)
LPC (USCS)	Classification based on USCS	At, Ap
GTR	French earthworks methods	A3, A4

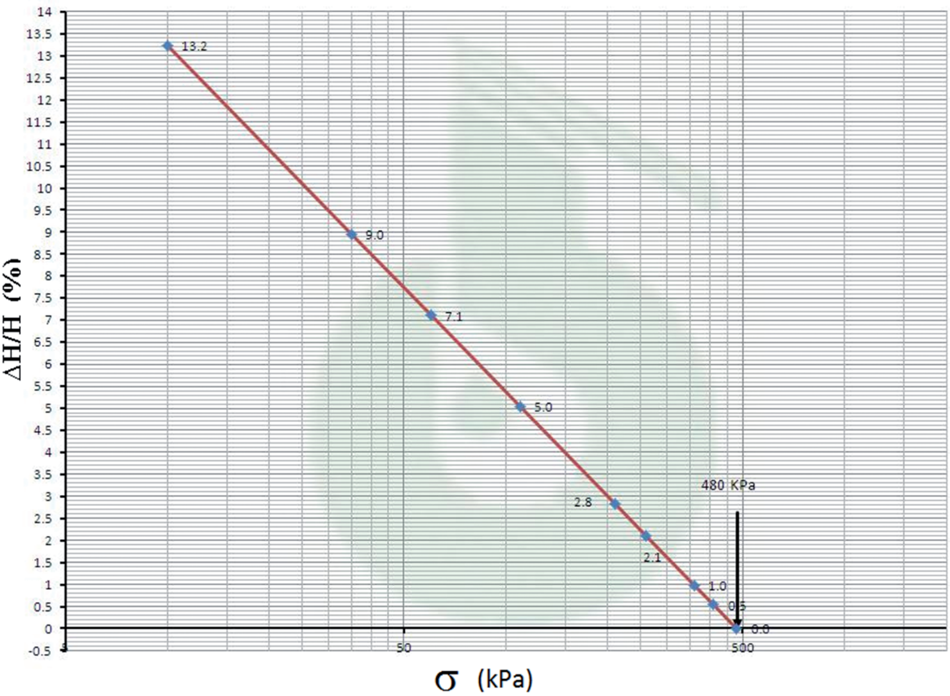


3.3. Measurement and characterization of swelling in the laboratory

Swelling and compressibility tests using an oedometer were conducted at the Laboratory of Public Works of the East (LTP Est).

Graphical deduction of the swelling index (Cg) values allows for the identification of swelling in the compressibility test. Preconsolidation pressure has the greatest effects on the swelling clay pressure of sensitive soils in Tebessa province [Berrah et al. 2021]. Apart from normally consolidated soils, most swelling soils show two characteristics: high over-consolidation (consolidation pressure ranging from 0.3 to 0.8 MPa) and a high swelling index. Once the swelling index exceeds 0.07, issues may arise with foundation uplift.

Swelling pressure. The Δh/hi curve is plotted as a function of applied pressure. An interpolation line between different points is drawn to estimate the pressure at which swelling is zero: this is the swelling pressure (Fig. 7).



Source: Authors' own study

Fig. 7. Oedometer swelling pressure curve Ps (kPa)

3.4. Determination of soil mineralogy (clay fraction)

Expansion potential is based on the estimated mineralogy of the soil [Badenhorst 2017]. A formation will be more sensitive to this phenomenon if its clay fraction contains a high proportion of 'swelling' clay minerals [Wilson et al. 2014]. Indeed, some clay minerals have a significantly higher propensity to shrink-swell than others [Deshmukh et al. 2012]. These include mainly smectites (montmorillonites), certain interstratified clay minerals, vermiculite, and some chlorites. For smectites, swelling, and consequently shrinkage, are more significant when they contain sodium instead of calcium. It is therefore possible to identify expansive soils and refine existing empirical formulas by studying their mineralogy. However, this identification is considered less practical, and may be slightly more costly.

Table 2. Calculation of total clay percentage in each sample

Caption	Legend	Angle 2-Theta	Intensity count	FC	Corrected intensity	Relative %
Ech 01						
d = 4.46535	clay total	19.87	23.50	20.00	470.00	56.11
d = 4.25929	gypse	20.84	36.90	0.40	14.76	1.76
d = 3.34164	quartz	26.66	118.00	1.00	118.00	14.08
d = 3.03164	calcite	29.44	139.00	1.65	229.35	27.38
d = 2.69419	anhydrite	33.23	5.43	1.00	5.43	0.64
Ech 02						
d = 3.34148	quartz	26.66	51.00	1.00	51.00	6.09
d = 4.46851	clay total	19.87	23.50	20.00	470.00	56.16
d = 3.03096	calcite	29.44	183.00	1.65	301.95	36.08
d = 4.24496	gypse	20.84	35.00	0.40	14.00	1.67

3.4.1. Percentage of interstratified minerals (presence of swelling minerals)

The mineralogical criterion is based on the average percentage of swelling minerals (illite-smectite interstratifications) present in the clay phase. Graphs of 14 samples collected from the studied region were based on a X-ray analysis. The calculated results are presented in Table 3. The graph in (Fig. 8) allows for the estimation of swelling percentage based on the measurement of the (v/p) parameter (the ratio between volume (V) and peak proportion (P).

Table 3. Swelling percentage in smectites and interstratifications

<table>
<tr><th>Peaks (d)</th><th>Mineral</th><th>Intensity</th><th>Corrected intensity</th><th>Percentage (%)</th><th>Ratio (V/P)</th><th>Swelling (%)</th></tr>
<tr><td colspan="7">Ech 01</td></tr>
<tr><td>16.87</td><td>smectite</td><td>140</td><td>35</td><td>55</td><td rowspan="2">0.86</td><td rowspan="2">93</td></tr>
<tr><td>7.13</td><td>kaolinite</td><td>40</td><td>28</td><td>45</td></tr>
<tr><td colspan="7">Ech 02</td></tr>
<tr><td>16.58</td><td>smectite</td><td>142</td><td>35</td><td>58</td><td rowspan="2">0.89</td><td rowspan="2">95</td></tr>
<tr><td>7.15</td><td>kaolinite</td><td>35</td><td>25</td><td>42</td></tr>
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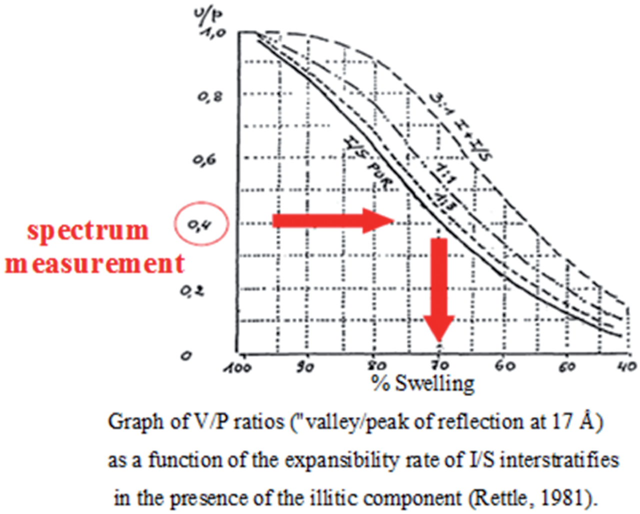

Source: Thorez [1976]

Fig. 8. v/p ratio and smectite content in illite-smectite interstratification

4. Conclusion

The comprehensive geotechnical and mineralogical analysis conducted in the Tebessa region in Algeria provides insight into on the complex behavior of sensitive soils prone to swelling. By integrating laboratory identification tests, mechanical tests, and mineralogical analyses, this study provides valuable insights into the swelling potential of soils prevalent in the area.

Geotechnical investigations revealed that the sensitive soils in the Tebessa region predominantly belong to the highly plastic clayey categories, with medium to extremely high swelling potential. Atterberg limits and mechanical tests further confirmed the susceptibility of these sensitive soils to swelling.

Mineralogical analysis through X-ray diffraction identified a significant presence of smectites in the soil samples, known for their high swelling potential, especially when containing sodium. The percentage of interstratified minerals, particularly illite-smectite interstratifications, was quantified, providing additional insights into the swelling behavior of the soils.

The findings of this study have significant implications for construction activities and infrastructure development in the Tebessa region. By understanding the swelling potential of soils and the mineralogical composition related to this phenomenon, informed decisions can be made to mitigate the risks associated with soil swelling, ensuring the sustainability and resilience of infrastructure projects.

Based on the findings of this study, researchers can develop advanced numerical models to simulate the behavior of clayey soils, incorporating parameters such as mineralogy, pore-water chemistry, and stress history. These models can help predict soil responses to different engineering activities and environmental factors, supporting the design of more resilient structures.

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