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Physical Characteristics of Expansive Clay Soil of the Bobonaro Formation at Km 68 Takari, Kupang Regency

Paulus Sianto

Department of Civil Engineering, Faculty of Engineering, Universitas Katolik Widya Mandira, Indonesia

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CORRESPONDENCE

Paulus Sianto

E-mail: paul.sianto.unwira@gmail.com

A B S T R A C T

Periodic damage to road infrastructure on Timor Island, particularly along the Takari Highway in Kupang Regency, is generally triggered by the poor geotechnical characteristics of the subgrade. This study aims to isolate and analyze the basic physical characteristics and initial swelling potential of the expansive clay soil from the Bobonaro Formation at KM 68 Takari. The laboratory experimental method was conducted to test soil index properties based on SNI standards, followed by swell testing at five variations of initial moisture content (17.05% to 18.85%) using two compaction energy levels (35 and 65 blows). The physical results show that the soil is classified as CH (Fat Clay) according to USCS and A-7-6 according to AASHTO, featuring a high plasticity index of 35.06% and a clay fraction of 47.69%. In the swell test, higher compaction energy consistently generated larger swelling percentages. This study successfully identified a critical finding in the form of a non-linear fluctuation pattern, where the maximum peak swelling of 5.77% (High category) occurred at a moisture content of 18.40% (wet side of OMC). In conclusion, conditioning at the critical moisture content of 18.40% must be avoided during field compaction to minimize the risk of pavement deformation. Contribution: This study contributes a site-specific physical and swelling characterization of the previously undocumented Bobonaro clay along the Takari corridor and identifies a novel non-linear swelling-versus-moisture pattern that departs from the conventional monotonic model reported in prior expansive soil literature. These insights provide local infrastructure practitioners and pavement designers in Kupang Regency with an actionable critical moisture threshold to avoid during subgrade compaction, directly supporting the journal's focus on practical, locally grounded civil engineering solutions.

INTRODUCTION

The deterioration of land transportation infrastructure, particularly highway pavements across Timor Island, East Nusa Tenggara, is frequently attributed to the instability of the supporting subgrade soils (Elsy E. Hangge, Karels, and Kapitan 2022; Liu, Tri M. W. Sir, and Elia Hunggurami 2025; Tamelan et al. 2024). Among the geological formations encountered in this region, the Bobonaro Formation is widely recognized as one of the most problematic due to its unfavorable geotechnical characteristics (Das and Sobhan 2016). Soils derived from this formation are generally dominated by highly expansive clay minerals, which undergo substantial volumetric changes in response to fluctuations in moisture content (Hardiyatmo 2014). These adverse physical characteristics often induce severe pavement distress, ranging from undulating surface cracking to significant differential settlement, thereby disrupting major transportation corridors, including the Takari Highway, which serves as the principal transportation artery of Kupang Regency (Fernandez 2018; Salu et al. 2025).

From a theoretical perspective, the expansive behavior of soils is governed primarily by their index properties and particle-size composition. Soils containing high proportions of pure clay fractions together with elevated Plasticity Index (PI) values generally possess minerals with exceptionally large specific surface areas capable of adsorbing substantial quantities of water molecules (Chen 1988). As water infiltrates the soil structure, hydration occurs within the interlayer spaces of clay mineral assemblages, generating considerable swelling pressure

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at the macroscopic scale (Fernandez 2018). Conversely, during prolonged dry seasons, evaporation of the natural soil moisture induces pronounced volumetric shrinkage, producing extensive desiccation cracks that substantially weaken the physical stability of the subgrade (E. Hangge, Pah, and Bei 2025). Consequently, a comprehensive evaluation of the soil's fundamental physical properties is indispensable before implementing any mechanical ground improvement measures in the field (Elsy Elisabet Hangge, Cornelis, and Peni 2024).

Numerous previous investigations have attempted to characterise the engineering behaviour of soils in Kupang Regency to address these geotechnical complexities. Comparative studies of expansive soils within neighbouring areas have demonstrated a high degree of sensitivity to different compaction regimes (Salu et al. 2025). Furthermore, investigations into the stability and bearing capacity of local clay soils consistently reveal a significant reduction in shear strength as the degree of water saturation increases (Fernandez 2018; Ramdani et al. 2026; Sir et al. 2026). Comprehensive evaluations of pavement foundation layers throughout Kupang Regency have likewise confirmed that, without an accurate understanding of the soil's physical characteristics, recurrent pavement failures are likely to persist (Elsy E. Hangge, Karels, and Kapitan 2022). The fluctuating shrinks–swell behavior associated with varying compaction conditions therefore requires isolated physical analyses to establish a fundamental understanding of the governing limits of the soil's index properties (Nelson and Miller 1992).

Accordingly, this study aims to provide a comprehensive analysis of the physical characteristics and initial swelling potential of expansive clay soils belonging to the Bobonaro Formation, using a specific case study located at KM 68 Takari, Kupang Regency. The scope of this article is deliberately confined to the investigation of the soil's index properties including natural moisture content, specific gravity, Atterberg limits, and particle-size distribution as well as laboratory swell tests conducted under various initial moisture contents and two levels of compaction energy (35 and 65 blows). By adopting this focused approach, the study seeks to establish a rigorous physical characterization of the soil as a primary scientific reference while simultaneously providing a foundation for subsequent investigations into its mechanical behavior, including California Bearing Ratio (CBR) and shear strength, in future publications.

RESEARCH METHODS

Relationship between the type of analysis and data requirements

This case study was deliberately designed as an isolated investigation to examine the macroscopic physical characteristics and the initial swelling potential of expansive clay soils without incorporating mechanical strength testing. To achieve these objectives, the analytical framework was divided into two principal stages. The first stage comprised an analysis of the soil index properties, which required primary data including the natural moisture content, specific gravity, particle-size distribution (clay, silt, and sand fractions), and the Atterberg limits (liquid limit, plastic limit, plasticity index, and shrinkage limit). The second stage focused on analysing the expansive behaviour of the soil, requiring primary data on its swelling response, expressed as the percentage of volumetric expansion resulting from variations in laboratory-controlled initial moisture conditions.

Study location, materials, and experimental equipment

This investigation employed a laboratory-based experimental approach using disturbed soil samples collected from a specific location along KM 68 of the Takari Highway, Kupang Regency, East Nusa Tenggara Province. The principal testing material consisted of natural clay soil originating from the local Bobonaro Formation. Evaluation of the soil's fundamental physical properties was carried out by qualified laboratory personnel using standard geotechnical testing equipment, including moisture-content containers, pycnometer bottles, a standard sieve set, hydrometer testing apparatus, a Casagrande liquid-limit device, and a glass plate for plastic-limit determination. The swelling characteristics were investigated using a laboratory compaction mould, a manual compaction hammer, and a dial gauge integrated with a laboratory swelling apparatus designed for specimen immersion and deformation measurement.

Laboratory testing procedures and reference standards

All laboratory procedures for determining the physical properties of the soil and preparing compacted specimens were conducted in strict accordance with the applicable Indonesian National Standards (SNI), as follows:

1. Determination of the natural moisture content was performed in accordance with SNI 1965:2019 (Badan Standarisasi Nasional 2019).
2. Determination of the specific gravity (Gs) followed SNI 1964:2008 (Badan Standarisasi Nasional 2008a).
3. Particle-size distribution analysis using the hydrometer method was conducted in accordance with SNI 3423:2008 (Badan Standarisasi Nasional 2008e).
4. Determination of the Liquid Limit (LL) followed SNI 1967:2008 (Badan Standarisasi Nasional 2008c).
5. Determination of the Plastic Limit (PL) and calculation of the Plasticity Index (PI) were performed using soil specimens passing the No. 40 sieve, in accordance with SNI 1966:2008 (Badan Standarisasi Nasional 2008b).
6. Determination of the Shrinkage Limit (SL) followed SNI 3422:2008 (Badan Standarisasi Nasional 2008d).

For the swelling tests, the soil specimens were first compacted at five different initial moisture contents, namely 17.05%, 17.50%, 17.95% (representing the Optimum Moisture Content, OMC), 18.40%, and 18.85%. Each moisture-content condition was prepared using two different levels of compaction energy, consisting of 65 blows per layer to represent high compaction energy and 35 blows per layer to represent low compaction energy. Immediately after compaction, each specimen was

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placed into the swelling apparatus and submerged in water. The maximum percentage of vertical expansion, expressed as ΔH/H, was measured periodically until no further deformation was observed and a constant swelling condition had been reached.

Data interpretation techniques

The analytical results were interpreted comprehensively to characterize the physical degree of soil expansiveness (Badan Standarisasi Nasional 2008b). The basic index-property data (table 1) were initially plotted on the Plasticity Chart according to the Unified Soil Classification System (USCS) and the AASHTO Soil Classification System to determine the engineering classification and subgrade suitability of the soil (Badan Standarisasi Nasional 2008c; E. Hangge, Pah, and Bei 2025). Subsequently, the swelling-test results (table 2) were interpreted graphically by examining the relationship between the maximum swelling percentage and the variation in initial moisture content under both levels of compaction energy. The resulting swelling percentages were then compared with the empirical classification proposed by Chen (1988) to determine the actual degree of physical expansiveness exhibited by the Bobonaro Formation clay at KM 68 Takari (Salu et al. 2025).

Ethical Considerations

This study involved laboratory testing of disturbed soil samples and did not include human participants or experimental animals. Consequently, ethical approval from a research ethics committee was not required. Field sampling and all laboratory investigations were conducted with the permission of, and using the facilities provided by, the Civil Engineering Laboratory, Faculty of Engineering, Widya Mandira Catholic University.

This section presents the principal and strategically significant findings obtained from the compilation of laboratory testing data. The discussion subsequently examines the engineering implications of the identified physical properties of the subgrade with respect to pavement performance. Furthermore, the experimental investigation revealed additional findings beyond those initially hypothesized; these are explicitly presented and discussed as important supplementary contributions of the present study.

Fundamental index properties of the soil

The principal and strategically significant information obtained from the compilation of laboratory test results on the fundamental physical properties of the clay soil collected from the case study location at KM 68 Takari, Kupang Regency, is summarized in table 1.

Based on the physical property data presented in table 1, the Plasticity Index (PI) was calculated using the mathematical relationship between the Atterberg limits as follows:

$PI = LL – PL$

where:

PI = Plasticity Index (%)

LL = Liquid Limit (%)

PL = Plastic Limit (%)

Application of Equation (1) yielded an average Plasticity Index (PI) of 35.06%. The particle-size distribution data further indicate that the average percentage passing the No. 200 sieve reached 55.68%, confirming that the soil is predominantly composed of fine-grained particles (>50%). Moreover, hydrometer analysis revealed that the pure clay fraction constitutes a highly dominant proportion of the soil, averaging 47.69%.

When the average Liquid Limit (LL) of 61.74% and Plasticity Index (PI) of 35.06% are plotted on the Plasticity Chart, the resulting coordinates lie conclusively above the A-line, placing the material within the CH (Fat Clay/High Plasticity Clay) classification according to the Unified Soil Classification System (USCS) (Candra et al. 2022; E. Hangge, Pah, and Bei 2025). Furthermore, based on the criteria of the AASHTO Soil Classification System, the material satisfies the requirements for classification as Group A-7-6 (Das and Sobhan 2016). These findings provide compelling physical evidence that the subgrade soil encountered at KM 68 Takari belongs to the Bobonaro Formation, exhibiting engineering characteristics that are highly unsuitable for pavement construction when subjected to uncontrolled moisture conditions (Das and Sobhan 2016; Hardiyatmo 2014; Titu-Eki and Dethan 2023).

Table 1. Summary of physical properties of clay soil from KM 68 Takari

No	Test Parameter	Symbol	Unit	Sample A	Sample B	Sample C	Average
1	Natural Moisture Content	Wn	%	38.98	39.13	38.69	38.93
2	Specific Gravity	Gs	-	2.45	2.50	2.62	2.52
3	Liquid Limit	LL	%	61.78	62.05	61.40	61.74
4	Plastic Limit	PL	%	26.71	27.25	26.10	26.69
5	Plasticity Index	PI	%	35.07	34.80	35.30	35.06
6	Shrinkage Limit	SL	%	48.61	48.78	47.90	48.43
7	Passing No. 200 Sieve	-	%	55.65	56.84	54.55	55.68
8	Clay Fraction	-	%	47.68	47.90	47.50	47.69
9	Silt Fraction	-	%	50.36	49.90	50.80	50.35
10	Sand Fraction	-	%	1.96	2.20	1.70	1.95

Characteristics of the initial expansive behavior (Swelling)

The strategic results obtained from the experimental investigation of swelling potential under varying initial moisture contents and two levels of manual compaction energy (35 and 65 blows) are presented in table 2.

Table 2. Swelling potential of Takari Clay Soil under different compaction conditions

No	Compaction Energy	Initial Moisture Content (%)	Swelling (%)	Degree of Expansiveness (Chen, 1988)
1	65 Blows	17.05	1.05	Medium
2		17.50	3.53	Medium
3		17.95 (OMC)	2.43	Medium
4		18.40	5.77	High
5		18.85	3.72	Medium
6	35 Blows	17.05	0.77	Medium
7		17.50	2.63	Medium
8		17.95 (OMC)	1.68	Medium
9		18.40	3.13	Medium
10		18.85	2.56	Medium

The graphical presentation shown in figure 1 provides a detailed illustration of the physical response of the expansive clay during compaction. A clear and consistent trend can be observed whereby specimens compacted using the higher compaction energy (65 blows) exhibited greater swelling percentages than those compacted using the lower energy (35 blows) at every corresponding moisture-content level. This observation is consistent with the well-established relationship between soil density and swelling behavior in expansive clays reported in previous studies (Misdi 2024). This behavior can be explained by the fact that higher compaction energy substantially reduces the soil's physical void ratio while forcing the clay particles of the Bobonaro Formation into a considerably denser arrangement. Consequently, when the compacted specimens subsequently come into contact with free water during immersion, the release of the accumulated internal stresses manifests as more pronounced macroscopic swelling deformation (Nelson and Miller 1992).

Additional significant finding: A Non-Linear fluctuation pattern

This study successfully identified a previously unreported phenomenon that extends beyond the conventional theoretical assumption that swelling decreases linearly as the initial moisture content increases (Uba, Sudjianto, and Suraji 2021)]. As illustrated in figure 1, the swelling curves exhibit a distinct fluctuation pattern. The swelling percentage initially declines at the Optimum Moisture Content (OMC) of 17.95%, but subsequently increases sharply to reach a maximum swelling peak at an initial moisture content of 18.40%, attaining 5.77% under 65 blows of compaction and 3.13% under 35 blows.

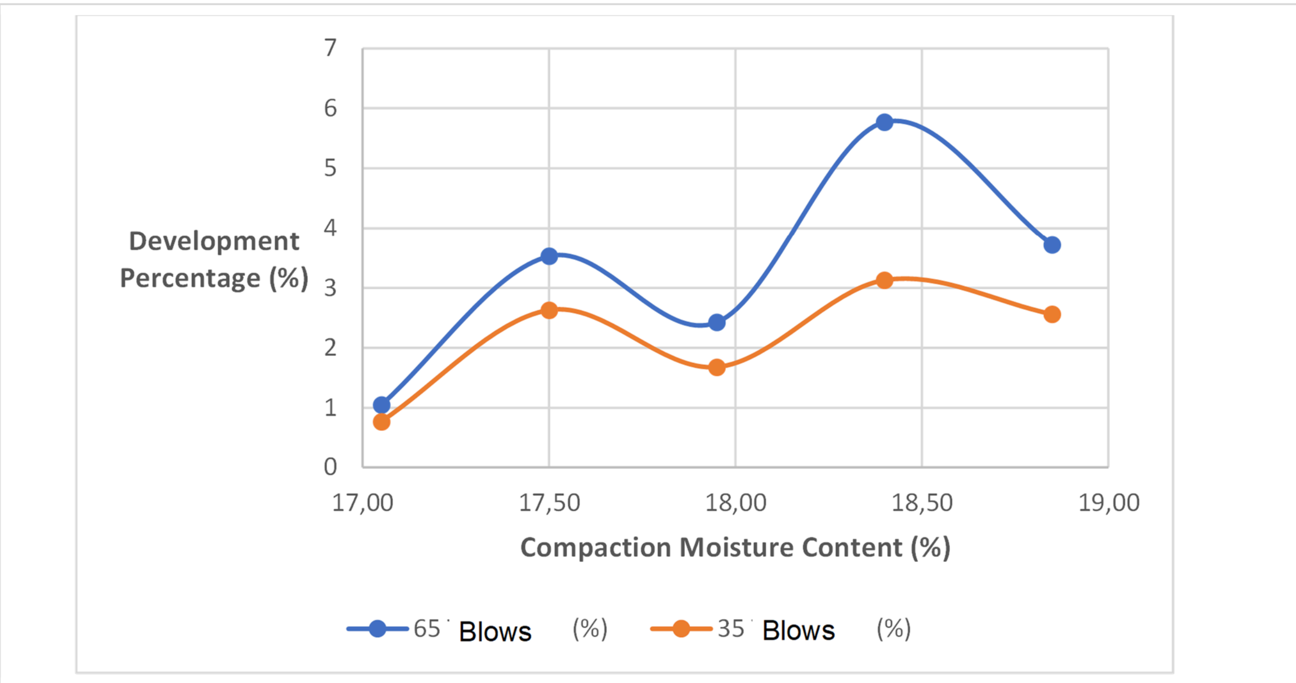

Figure 1. Fluctuation of Swelling percentage with variations in initial Moisture Content

This additional and significant finding provides physical evidence that, under an initial moisture content of 18.40%, corresponding to the wet side of the Optimum Moisture Content (OMC), the arrangement of soil particles reaches a microscopically unstable

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condition that is particularly susceptible to water infiltration. Under these circumstances, immersion in water promotes extensive disintegration of the interparticle bonds within the locally occurring montmorillonite mineral assemblages, thereby triggering an aggressive swelling response. As the initial moisture content increases further to 18.85%, however, the swelling percentage declines because a substantial proportion of the soil pore spaces has already become occupied by water prior to the commencement of the swelling test, thereby limiting the additional hydration capacity of the clay minerals (Misdi 2024). According to the empirical classification proposed by Chen (1988), the expansive clay of the Bobonaro Formation at KM 68 Takari exhibits an expansiveness ranging from the Low category to the High category, with the maximum swelling of 5.77% exceeding the 5% threshold for highly expansive soils (Chen 1988).

Implications of the study

The investigation of the physical characteristics of the expansive clay belonging to the Bobonaro Formation at KM 68 Takari extends beyond the mere reporting of laboratory parameters and carries significant technical implications for addressing broader socio-economic challenges in Kupang Regency. The Takari Highway constitutes the principal logistics corridor connecting Indonesia and Timor-Leste and serves as one of the most critical transportation arteries supporting economic activities throughout Timor Island. Recurrent pavement failures resulting from the shrink–swell behavior of the expansive subgrade have long contributed to inefficient public expenditure, increased traffic accidents, and disruptions to the distribution of food supplies and healthcare services for remote communities. Consequently, the accurate physical characterization presented in this study contributes directly to breaking this recurring cycle of infrastructure deterioration, thereby supporting efforts to maintain the quality of life of the affected population (Salu et al. 2025).

From a practical engineering perspective, the identification of a non-linear swelling pattern, with a maximum swelling value of 5.77% (classified as High) occurring at a compaction moisture content of 18.40%, provides an important preventive recommendation for government agencies and highway contractors. The logical implication is that subgrade compaction within the Takari area should not be performed when the soil moisture content approaches 18.40%, as this condition presents the greatest potential for severe geomorphological deterioration of pavement structures during the rainy season (Salu et al. 2025). Instead, field operations should be directed towards safer moisture conditions or be accompanied by appropriate physical soil stabilization techniques (Nelson and Miller 1992).

A thorough understanding of these critical index properties and swelling characteristics also enables pavement thickness to be designed with greater precision and efficiency (Badan Standarisasi Nasional 2008c). Accordingly, the isolated scientific contribution of this study provides an essential foundation for enhancing the long-term resilience of public infrastructure, ultimately contributing to safer transportation systems, improved road-user safety, and greater socio-economic stability within Kupang Regency (Elsy E. Hangge, Karels, and Kapitan 2022).

Limitations of the study

The findings of this study should be interpreted in light of several methodological limitations. First, the scope of the investigation was intentionally confined to the evaluation of the soil's physical characteristics and its initial swelling potential (swelling percentage), without incorporating mechanical strength tests such as the California Bearing Ratio (CBR) or direct shear tests. Consequently, the swelling pressure generated by the expansive soil and its direct influence on pavement bearing capacity could not be quantified within the scope of the present investigation. Second, the study utilized only three sampling locations (Samples A, B, and C) obtained from a single site at KM 68 Takari. Therefore, extrapolation of the identified non-linear swelling pattern to other sections of the Bobonaro Formation should be undertaken with caution and ideally verified through investigations involving a larger number of sampling locations. Third, the swelling tests were conducted under controlled laboratory conditions using manual compaction procedures. Actual field compaction, which commonly employs heavy mechanical equipment, may produce different soil densities, void ratios, and swelling responses. Consequently, the critical moisture content identified in this study (18.40%) should be regarded as site-specific and indicative, requiring further validation through subsequent mechanical investigations involving CBR and shear strength testing, as proposed by the authors for future research.

CONCLUSION

The principal conclusions derived from this investigation of the physical characteristics of the expansive clay soil of the Bobonaro Formation at KM 68 Takari, Kupang Regency, can be summarized as follows: (1) Physical Index Characteristics: Based on the laboratory determination of the fundamental physical properties, the soil at KM 68 Takari is consistently classified as CH (Fat Clay/High Plasticity Clay) according to the Unified Soil Classification System (USCS) and as Group A-7-6 under the AASHTO Soil Classification System. The soil is predominantly composed of fine-grained particles (55.68%), with a highly dominant clay fraction of 47.69%, and exhibits a high Plasticity Index (PI) of 35.06%. Collectively, these physical indicators confirm that the material possesses poor engineering suitability as a highway subgrade; (2) Shrink–Swell Behavior: Specimens compacted under higher compaction energy (65 blows) consistently exhibited greater swelling percentages, reaching the High expansiveness category, than those compacted using lower compaction energy (35 blows) under identical moisture-content conditions. This finding provides a new theoretical insight by demonstrating that the reduction in the physical void ratio of the Bobonaro Formation clay actually intensifies the repulsive interactions among clay mineral particles when the soil comes into contact with free water, thereby producing a more aggressive swelling response; (3) Theoretical Advancement (Identification of a Non-Linear Fluctuation Pattern): This study successfully identified a scientific advancement in the form of a non-linear fluctuation pattern in the swelling curve. Contrary to the conventional theoretical expectation, the maximum swelling potential did not occur under the driest initial moisture condition. Instead, the swelling curve reached its peak at an initial moisture content of 18.40%, corresponding to the wet side of the Optimum Moisture Content (OMC), with maximum swelling values of 5.77% under 65 blows and 3.13% under 35 blows of compaction.

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