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Moisture vulnerability of lateritic soil in bauxite mine haul roads: Laboratory evidence and a performance-based field trial framework

Đặc tính nhạy nước của đất lateritic trong đường vận chuyển mỏ bauxite: Bằng chứng thí nghiệm trong phòng và khung thử nghiệm hiện trường theo hiệu năng

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ABSTRACT

Lateritic soil is a locally available material with potential use in haul-road pavement layers in tropical mining regions, particularly when improved using suitable binders. However, under wet-season conditions, such soils may experience moisture-induced serviceability loss, including softening, mud formation, surface instability and reduced trafficability under repeated heavy truck loading. This study investigates the moisture vulnerability of lateritic soil from the Nhan Co bauxite mine area in Lam Dong Province, Vietnam and evaluates the laboratory-based feasibility of cement-polymer stabilization for haul-road material application. The natural soil exhibited relatively favorable CBR values under laboratory compaction; however, its index properties, high fine content and qualitative loss of integrity of untreated compacted specimens under water immersion indicate that CBR should not be used as a stand-alone performance indicator. Based on this evidence, the diagnostic concept of a “CBR-satisfactory but moisture-vulnerable lateritic soil” is proposed. Cement-polymer stabilized mixtures showed clear improvements in unconfined compressive strength, splitting tensile strength and elastic modulus with curing age, demonstrating enhanced laboratory mechanical response. Nevertheless, these results are interpreted as laboratory-based feasibility evidence rather than field-

validated performance. A performance-based field trial framework is therefore proposed to guide future validation, integrating initial bearing capacity, moisture vulnerability, stabilization performance, constructability, construction quality control, drainage condition and wet-season serviceability monitoring. The study contributes a diagnostic and laboratory-to-field decision framework for evaluating moisture-vulnerable lateritic soils before full-scale application in stabilized haul-road pavement layers.

Keywords: Lateritic soil; CBR; moisture vulnerability; cement-polymer stabilization; bauxite mine haul road; performance-based field trial.

TÓM TẮT

Đất lateritic là nguồn vật liệu tại chỗ có tiềm năng sử dụng cho các lớp kết cấu đường vận chuyển trong vùng khai thác mỏ nhiệt đới, đặc biệt khi được cải thiện bằng các chất kết dính phù hợp. Tuy nhiên, trong điều kiện mùa mưa, loại đất này có thể bị suy giảm khả năng phục vụ do tác động của nước, thể hiện qua hiện tượng mềm hóa, hóa bùn, mất ổn định bề mặt và giảm khả năng lưu thông dưới tác dụng lặp lại của xe tải nặng. Nghiên cứu này đánh giá tính nhạy nước của đất lateritic lấy từ khu vực mỏ bauxite Nhân Cơ, tỉnh Lâm Đồng, Việt Nam, đồng thời xem xét tính khả thi trong phòng thí nghiệm của giải pháp gia cố xi măng-polymer cho ứng dụng làm vật liệu đường vận chuyển mỏ. Đất tự nhiên cho thấy các giá trị CBR tương đối thuận lợi trong điều kiện đầm chặt thí nghiệm. Tuy nhiên, các đặc trưng chỉ số, hàm lượng hạt mịn cao và hiện tượng mất toàn vẹn định tính của mẫu đất đầm chặt không gia cố khi ngâm nước cho thấy CBR không nên được sử dụng như một chỉ tiêu hiệu năng độc lập. Trên cơ sở các bằng chứng này, nghiên cứu đề xuất khái niệm chẩn đoán “đất lateritic có CBR tương đối đạt nhưng nhạy nước”. Các hỗn hợp đất gia cố xi măng-polymer cho thấy sự cải thiện rõ rệt về cường độ nén không nở hông, cường độ ép chẻ và mô-đun đàn hồi theo tuổi bảo dưỡng, qua đó thể hiện sự cải thiện về đáp ứng cơ học trong điều kiện phòng thí nghiệm. Tuy nhiên, các kết quả này chỉ được diễn giải như bằng chứng về tính khả thi trong phòng thí nghiệm, không phải là hiệu năng đã được kiểm chứng ngoài hiện trường. Do đó, nghiên cứu đề xuất một khung thử nghiệm hiện trường theo hiệu năng nhằm định hướng cho bước kiểm chứng trong tương lai, tích hợp sức chịu tải ban đầu, tính nhạy nước, hiệu quả gia cố, khả năng thi công, kiểm soát chất lượng thi công, điều kiện thoát nước và theo dõi khả năng phục vụ trong mùa mưa. Nghiên cứu đóng góp một khung chẩn đoán và ra quyết định từ phòng thí nghiệm đến hiện trường để đánh giá đất lateritic nhạy nước trước khi áp dụng đại trà cho các lớp kết cấu đường vận chuyển mỏ được gia cố.

Từ khóa: Đất lateritic; CBR; tính nhạy nước; gia cố xi măng-polymer; đường vận chuyển mỏ bauxite; thử nghiệm hiện trường theo hiệu năng.

1. INTRODUCTION

Mine haul roads are critical infrastructure in open-pit mining because they directly influence the continuity, safety and cost-efficiency of material transportation. Unlike conventional roads, haul roads are repeatedly exposed to heavy-duty truck traffic and severe operating conditions, which can accelerate deterioration when pavement layers lose stiffness or serviceability [1]. In many mining areas, the use of locally available soils is technically and economically attractive because it reduces the demand for imported granular aggregates and lowers construction logistics. Lateritic soils, which are widely distributed in tropical regions, have therefore been increasingly considered for pavement and haul-road applications after suitable improvement or stabilization [2, 3]. However, their engineering performance is strongly affected by plasticity, fine-particle content, compaction condition, moisture regime, and wetting-drying exposure [2-5]. Thus, lateritic

soils should be assessed not only as locally available construction materials, but also as moisture-sensitive geomaterials whose field behavior may differ from their apparent laboratory bearing capacity.

Moisture-induced deterioration is particularly important for unsealed or lightly surfaced haul roads in tropical environments. Seasonal wetting can increase saturation, reduce soil suction, soften fine-grained pavement layers and promote rutting, settlement, or loss of trafficability under repeated truck loading [1]. Previous studies on mine haul roads and stabilized lateritic pavement materials have shown that moisture variation, wetting-drying cycles, fine content and binder effectiveness play decisive roles in deformation resistance and durability [1, 4-6]. The Nhan Co bauxite mine haul road in Đắk Nông Province, Vietnam, provides a relevant case context for this problem. The road is used to transport bauxite ore from the mining area to the bunker or processing plant area and is subjected to repeated heavy truck movements under wet-season exposure. As shown in Figure 1, project-specific field photographs provided by the Nhan Co plant illustrate wet-season serviceability problems, including surface mud formation, water accumulation, slipperiness and reduced trafficability. These observations indicate that the engineering concern is not limited to initial bearing capacity, but also involves the ability of the lateritic road material to maintain surface integrity and serviceability under moisture exposure and repeated heavy traffic. Since quantitative field monitoring data are not available in the current dataset, the Nhan Co case is used here as a project-specific background for laboratory-based assessment and future field-trial framework development, rather than as evidence of completed field validation.



Figure 1. Project-specific field photographs of the Nhan Co bauxite mine haul road under wet-season conditions, showing surface mud formation, water accumulation, and reduced trafficability. The photographs were provided by the Nhan Co plant and are used with permission

Although the California Bearing Ratio (CBR) is widely used to assess subgrade and pavement materials, it should not be interpreted as a stand-alone performance indicator for fine-grained or moisture-sensitive soils. CBR is influenced by soil classification, grading, plasticity, compaction characteristics, and moisture susceptibility; therefore, CBR-based assessment should be integrated with broader soil-property evaluation [7]. In this context, the present study adopts the diagnostic concept of a “CBR-satisfactory but moisture-vulnerable lateritic soil”, while leaving the detailed laboratory evidence for the subsequent experimental database and analysis sections. The objectives of this study are to characterize the natural lateritic soil from the Nhan Co bauxite mine, diagnose the discrepancy between laboratory bearing indicators and wet-season serviceability concerns, assess the laboratory feasibility of cement-polymer stabilization and propose a

performance-based field trial framework for future validation. The main contribution is a laboratory-to-field decision framework that integrates initial bearing capacity, moisture vulnerability, stabilization performance, constructability, quality control, drainage considerations, and future serviceability monitoring before full-scale implementation in wet tropical bauxite mine haul roads.

2. MATERIALS AND EXPERIMENTAL PROGRAM

2.1. Natural Lateritic Soil and Case Context

The material investigated in this study was a natural lateritic soil collected from the Nhan Co bauxite mine area in Đắk Nông, Vietnam as shown in the Figure 1. The soil represents a locally available material associated with the mine haul road context described in the Introduction. In this paper, the Nhan Co haul road is used as a project-specific case context for examining the relationship between laboratory soil properties, moisture vulnerability, and the need for a future performance-based field trial framework.

The experimental program was designed to characterize the natural lateritic soil and to evaluate the laboratory-based feasibility of cement-polymer stabilization. The natural soil was tested for index properties, compaction characteristics, CBR and swelling. Stabilized mixtures were then prepared using different cement contents combined with a polymer additive, while a cement-Geostab mixture was also included in the available dataset for comparison. The stabilized materials were evaluated through unconfined compressive strength, splitting tensile strength and elastic modulus tests.



Figure 2. Field sampling and visual condition of the natural lateritic soil at the Nhan Co bauxite mine, Đắk Nông Province, Vietnam: (a) collection of disturbed soil samples for laboratory testing; (b) view of the mine haul road surface at the sampling area and (c) close-up view of the lateritic soil texture. Photographs are used with permission

Within the scope of this study, the soil is treated as a project-specific lateritic material associated with the Nhan Co mine haul road context, rather than as a statistically representative material for all lateritic deposits in the region.

2.2. Index Properties, Compaction Characteristics, CBR and Swelling

The natural lateritic soil was characterized using standard laboratory tests. Particle size distribution was determined according to TCVN 4198:2014 [8], Atterberg limits according to TCVN 4197:2012 [9], natural moisture content according to TCVN 4196:2012 [10], specific gravity according to TCVN 4195:2012 [11], organic content according to ASTM D2974 [12], compaction characteristics according to TCVN 12790:2020 [13] and CBR according to TCVN 12792:2020 [14].

The index and compaction properties of the natural soil are summarized in Table 1. These data are presented as the experimental basis for subsequent interpretation. Their implications for moisture vulnerability are discussed later in the Results and Discussion section.

Table 1. Index properties and compaction characteristics of the natural lateritic soil

Properties	Units	Test results	Test Methods
Natural moisture content	%	29.70	TCVN 4196:2012
Specific gravity	-	2.773	TCVN 4195:2012
Organic content	%	19.3	ASTM D2974
Liquid limit, LL	%	54.85	TCVN 4197:2012
Plastic limit, PL	%	37.00	TCVN 4197:2012
Plasticity index, PI	%	17.85	TCVN 4197:2012
Passing 2.00 mm sieve	%	80.73	TCVN 4198:2014
Passing 0.075 mm sieve	%	54.54	TCVN 4198:2014
Maximum dry density, MDD	g/cm ³	1.653	TCVN 12790:2020
Optimum moisture content, OMC	%	22.06	TCVN 12790:2020

CBR and swelling were determined at three compaction levels, namely K95, K98, and K100. The results are given in Table 2. The apparent contrast between the CBR values and the moisture-sensitive characteristics of the soil is not interpreted in this section; it forms the basis for the moisture-vulnerability diagnosis in Section 3.1.

Table 2. CBR and swelling characteristics of the natural lateritic soil

Degree of compaction	Dry density condition	CBR	Swelling
K95	0.95 MDD	25.17%	0.41%
K98	0.98 MDD	30.70%	0.39%
K100	1.00 MDD	33.91%	0.35%

Untreated soil specimens were observed to become weak or disintegrated under soaked conditions. This observation is considered laboratory evidence of water-induced loss of integrity and is not presented as field failure or field validation.

2.3. Cement-Polymer Stabilized Soil Mixtures and Testing Program

The stabilization program included untreated lateritic soil and cement-treated mixtures prepared with a polymer additive. The main cement-polymer mixtures contained 8%, 10% and 12% cement by dry soil mass, combined with a polymer additive dosage of 3.75 L/m³ of compacted soil. The available dataset also included a mixture containing 10% cement combined with Geostab. The chemical composition of the polymer additive and Geostab is not available in the current dataset and is therefore not inferred.

Table 3. Stabilized soil mixtures included in the experimental database

Mixture ID	Soil condition	Cement content	Additive type	Reported additive dosage
UTS	Untreated lateritic soil	0%	None	Not applicable

8C-P	Cement-polymer stabilized soil	8%	Polymer additive	3.75 L/m ³ compacted soil
10C-P	Cement-polymer stabilized soil	10%	Polymer additive	3.75 L/m ³ compacted soil
12C-P	Cement-polymer stabilized soil	12%	Polymer additive	3.75 L/m ³ compacted soil

The stabilized mixtures were assessed using unconfined compressive strength, splitting tensile strength, and elastic modulus tests. The unconfined compressive strength test followed ASTM D1633 [15], the splitting tensile strength test followed TCVN 8862:2011 [16], and the elastic modulus test followed TCVN 9843:2013 [17]. The stabilized specimens were tested at curing ages of 3, 7, 14, and 28 days, depending on mixture and data availability. The current dataset does not provide complete information on specimen dimensions, mixing energy, mixing duration, curing temperature, curing humidity, or detailed field construction procedures; these details are therefore reported as unavailable rather than estimated.

Table 4. Summary of the laboratory testing program

Test parameters	Material condition	Test method	Role in this study
Particle size distribution	Natural soil	TCVN 4198:2014	Material characterization
Atterberg limits	Natural soil	TCVN 4197:2012	Moisture-vulnerability diagnosis
Natural moisture content	Natural soil	TCVN 4196:2012	Initial material condition
Specific gravity	Natural soil	TCVN 4195:2012	Basic soil property
Organic content	Natural soil	ASTM D2974	Material characterization
MDD and OMC	Natural soil	TCVN 12790:2020	Compaction behavior
CBR and swelling	Natural soil	TCVN 12792:2020	Bearing response and volume change
Unconfined compressive strength	Untreated and stabilized soils	ASTM D1633	Laboratory feasibility
Splitting tensile strength	Stabilized soils	TCVN 8862:2011	Tensile response
Elastic modulus	Stabilized soils	TCVN 9843:2013	Stiffness response

2.4. Proposed Field Trial Information

The project documentation also includes a proposed field trial configuration for future validation. The candidate section has a proposed length of 200 m and width of 13 m, corresponding to an approximate area of 2,600 m². The proposed structure consists of a 20 cm cement-polymer stabilized lateritic soil layer and a 3 cm upper surface layer of crushed stone or graded aggregate material. Surface slope and side drainage are

included as part of the proposed field-trial concept to reduce water accumulation on the running surface.

This field trial information is included only to define the future validation pathway. The proposed 200 m section has not been constructed, monitored, tested, or field-validated in the current study. No field performance data are available, including traffic volume, axle-load spectra, rainfall intensity, construction date, field density, field moisture, rut depth, settlement, drainage performance or long-term serviceability monitoring.

Table 5. Proposed field trial information for future validation

Item	Proposed value or description	Data status
Trial section length	200 m	Proposed only
Trial section width	13 m	Proposed only
Approximate area	2,600 m ²	Derived from proposed dimensions
Stabilized lateritic soil layer	20 cm	Proposed only
Upper surface layer	3 cm crushed stone or graded aggregate	Proposed only
Drainage provision	Surface slope and side drainage	Proposed design requirement
Construction / monitoring status	Not available	Future validation required
Traffic volume / axle load / rainfall record	Not available	Not provided in current dataset
Rut depth / settlement / field performance	Not available	Not provided in current dataset

The experimental database should be interpreted within the scope of the present study. Part of the laboratory mechanical data has been reported previously in a study on cement-TS Mika® VN stabilized soil [11]. In contrast to that work, the present paper uses the dataset to support a moisture-vulnerability diagnosis and to formulate a performance-based field trial framework for bauxite mine haul roads, rather than to re-optimize additive dosage or repeat the same mechanical-performance interpretation. The proposed 200 m trial section is therefore treated only as a future validation pathway and not as a completed field experiment.

3. RESULTS AND DISCUSSIONS

3.1. Moisture Vulnerability Diagnosis beyond CBR

The CBR results of the natural lateritic soil suggest an apparently favorable bearing response under controlled laboratory compaction. As shown in Table 2, the CBR increased from 25.17% at K95 to 30.70% at K98 and 33.91% at K100. The corresponding swelling values were low, ranging from 0.41% to 0.35%. From a conventional CBR-based perspective, these results may indicate that the compacted lateritic soil has a relatively adequate penetration resistance under laboratory conditions. However, for mine haul roads exposed to wet-season conditions, CBR should not be interpreted as a stand-alone indicator of material suitability. It reflects penetration resistance under a prescribed test condition, but does not fully capture the ability of a fine-grained lateritic material to

maintain integrity, stiffness and trafficability under prolonged moisture exposure and repeated heavy truck loading.

This limitation becomes clearer when the CBR results are considered together with the index properties of the soil. The natural lateritic soil had a liquid limit of 54.85%, plastic limit of 37.00%, plasticity index of 17.85% and 54.54% passing the 0.075 mm sieve. These values indicate a high fine-particle content and measurable plasticity, both of which may increase water retention and softening potential under wet conditions. The soil also had a natural moisture content of 29.70%, an optimum moisture content of 22.06% and a maximum dry density of 1.653 g/cm³. These data do not automatically imply that the material is unsuitable for all road applications, but they indicate that CBR alone is insufficient for evaluating its wet-season serviceability.

The most direct laboratory evidence of water sensitivity was obtained from the qualitative soaking observation. As shown in Figure 3, the compacted Proctor specimen of the untreated lateritic soil retained its shape before immersion but visibly lost integrity after approximately 5 min of water exposure. This observation is not treated as a standardized durability test, and it should not be interpreted as field validation or field failure. Nevertheless, it provides useful laboratory evidence that the untreated compacted soil may be vulnerable to water-induced loss of integrity. This behavior is particularly relevant to the Nhan Co haul road context, where wet-season serviceability rather than dry bearing capacity is the central engineering concern.

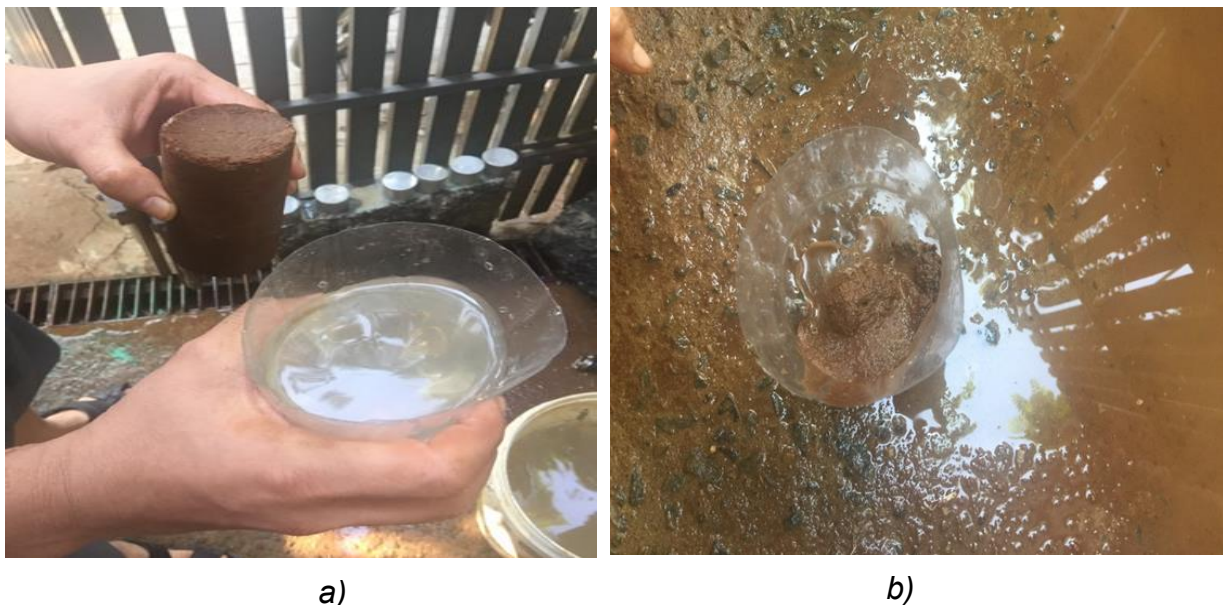


Figure 3. Qualitative laboratory observation of the untreated compacted lateritic soil from the Nhan Co bauxite mine under water exposure: a) compacted Proctor specimen before immersion; b) visible disintegration after approximately 5 min of soaking. This observation illustrates water-induced loss of specimen integrity and is not intended as a quantitative durability test. Photographs were taken by the authors

Taken together, the CBR, Atterberg limits, fine content and soaking observation support the diagnostic concept of a CBR-satisfactory but moisture-vulnerable lateritic soil. This concept refers to a material that exhibits relatively favorable CBR values under laboratory compaction but also shows moisture-sensitive index properties and water-induced loss of integrity under soaked conditions. It is not proposed as a new formal soil classification system. Rather, it is a diagnostic interpretation that helps bridge the gap between laboratory bearing capacity and wet-season serviceability. For the Nhan Co lateritic soil, this concept provides the technical basis for examining whether cement-

polymer stabilization can improve the mechanical response of the material before any field implementation is considered.

3.2. Laboratory-Based Feasibility of Cement-Polymer Stabilization

The stabilization program was evaluated as a laboratory-based feasibility assessment, not as a field validation study or a dosage optimization study. The purpose was to determine whether cement-polymer treatment could improve the mechanical response of the moisture-vulnerable lateritic soil diagnosed in Section 3.1. The untreated soil became weak or disintegrated under soaked conditions, whereas all cement-treated mixtures developed measurable compressive strength, splitting tensile strength, and elastic modulus after curing. This contrast indicates that cement-based treatment contributed to the formation of a bonded soil matrix under laboratory conditions.

As summarized in Figure 4 [18], the cement-polymer stabilized mixtures showed progressive improvements in UCS, STS, and elastic modulus with curing age, indicating enhanced mechanical response under laboratory conditions. This supports the feasibility of stabilization as a candidate improvement strategy for the moisture-vulnerable lateritic soil. Nevertheless, the figure should not be interpreted as evidence of field-validated performance, since long-term serviceability in mine haul roads depends on additional factors such as drainage efficiency, construction uniformity, field moisture condition, curing environment, and traffic loading.

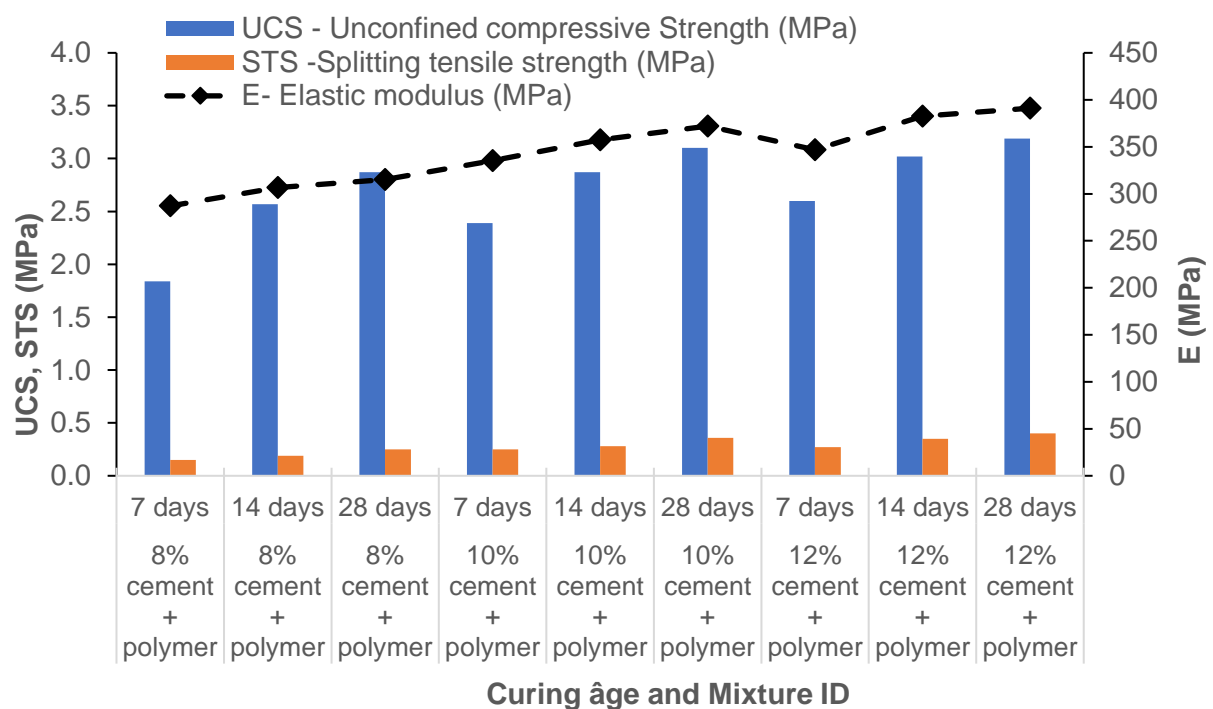


Figure 4. Laboratory mechanical properties of cement-polymer stabilized lateritic soil with different cement contents and curing ages: unconfined compressive strength (UCS), splitting tensile strength (STS) and elastic modulus (E). UCS and STS are plotted on the left vertical axis, while E is plotted on the right vertical axis [18]

The unconfined compressive strength results show a clear improvement in the stabilized mixtures. The 8% cement-polymer mixture reached 1.84 MPa at 7 days, 2.57 MPa at 14 days and 2.87 MPa at 28 days. The 10% cement-polymer mixture increased from 2.10 MPa at 3 days to 3.10 MPa at 28 days, while the 12% cement-polymer mixture increased from 2.34 MPa to 3.19 MPa over the same curing period. These results indicate that cement-based stabilization improved the compressive response of the soil under the tested laboratory conditions. However, the relatively small difference between the 10%

and 12% cement-polymer mixtures at 28 days should not be used alone to define an optimum dosage, because field constructability, drainage, shrinkage, curing, cost and serviceability were not evaluated in the current dataset.

The splitting tensile strength results provide complementary evidence of improved internal bonding. The 8% cement-polymer mixture increased from 0.16 MPa at 7 days to 0.25 MPa at 28 days. The 10% cement-polymer mixture increased from 0.21 MPa at 3 days to 0.36 MPa at 28 days, while the 12% cement-polymer mixture increased from 0.24 MPa to 0.40 MPa. This development suggests that stabilization improved the tensile-related resistance of the cemented soil matrix. For haul road materials, this is relevant because stabilized layers may experience tensile and shear-related stresses induced by wheel loading and differential deformation. Even so, laboratory splitting tensile strength should not be interpreted as direct evidence of field crack resistance, since actual cracking behavior depends on curing, shrinkage, moisture fluctuation, layer thickness, compaction and traffic loading.

The elastic modulus results further confirm the improvement in stiffness. The 8% cement-polymer mixture increased from 287.1 MPa at 7 days to 315.2 MPa at 28 days. The 10% cement-polymer mixture increased from 276.7 MPa at 3 days to 372.2 MPa at 28 days, while the 12% cement-polymer mixture reached 391.1 MPa at 28 days. These results are consistent with the strength development trends and suggest progressive stiffening of the cemented matrix during curing. For mine haul roads, improved stiffness may contribute to greater resistance against deformation under repeated truck loading. Nevertheless, the laboratory modulus values cannot be used as direct predictors of in-service deformation without field calibration.

The mechanical results indicate that cement-polymer stabilization is a feasible laboratory-based improvement strategy for the investigated lateritic soil. The stabilized mixtures developed compressive strength, tensile resistance, and stiffness, while the untreated soil lost integrity under soaked conditions. These results justify further field-oriented assessment, but they do not establish field durability, wet-season performance, or long-term trafficability. The laboratory findings should therefore be viewed as a basis for a structured field trial rather than as final design confirmation.

3.3. Proposed Performance-Based Field Trial Framework

Because the present study is based mainly on laboratory data, a performance-based field trial framework is proposed to guide future validation. The framework is built on the premise that material strength alone is insufficient for evaluating stabilized lateritic soil in wet tropical mine haul roads. A future trial should verify not only laboratory mechanical performance, but also constructability, moisture control, drainage effectiveness and serviceability under actual traffic and rainfall exposure.

The proposed framework consists of five linked components: Natural soil characterization, moisture-vulnerability diagnosis, laboratory stabilization feasibility, candidate field trial design and future field monitoring. The first component establishes the soil's index, compaction, CBR and swelling properties. The second identifies whether the material is CBR-satisfactory but moisture-vulnerable. The third determines whether stabilization improves mechanical response in the laboratory. The fourth translates the laboratory evidence into a candidate trial section. The fifth defines what must be monitored before any scale-up decision is made.

Table 6. Proposed performance criteria for future field validation

Performance group	Main indicators	Purpose of assessment	Interpretation level
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Initial bearing capacity	CBR, MDD, OMC, degree of compaction	Assess laboratory bearing and compaction behavior	Laboratory index evidence
Moisture vulnerability	LL, PI, fine content, soaked disintegration	Identify water-induced softening or loss of integrity	Laboratory diagnosis
Stabilization performance	UCS, splitting tensile strength, elastic modulus	Assess mechanical improvement after treatment	Laboratory feasibility
Constructability	Mixing depth, binder dosage, moisture control, compaction	Verify practical implementation	Future field QC
Drainage condition	Surface slope, side drainage, ponding control	Reduce water accumulation	Future field design requirement
Serviceability	Rutting, mud formation, potholes, trafficability	Validate haul-road performance	Future field monitoring

A future field trial should include a construction quality control plan. Key control items include surface preparation, soil moisture, cement spreading uniformity, polymer-water dosage, mixing depth, mixture homogeneity, compaction quality, surface finishing and early curing protection. These items are essential because non-uniform binder distribution, inadequate mixing, excessive moisture, or poor compaction may create weak zones that remain vulnerable to water ingress and traffic-induced deformation. Drainage control is equally important because the original problem is associated with wet-season serviceability loss.

Field monitoring should evaluate both material quality and road serviceability. At the material level, future monitoring should include field density, field moisture, and strength verification of field-prepared or extracted specimens. At the serviceability level, the monitoring should include rutting, local settlement, pothole development, mud formation, water ponding, cracking, trafficability after rainfall, and maintenance demand. Because the current dataset does not include rainfall records, traffic volume, or axle-load data, quantitative thresholds cannot be defined at this stage. These limits should be established before field implementation based on project requirements and operational data.

Future scale-up should be considered only if the trial section demonstrates satisfactory material quality, construction consistency, drainage function and wet-season serviceability. The decision should not be based solely on laboratory UCS, splitting tensile strength, elastic modulus or CBR. Instead, it should integrate laboratory indicators with field construction records, drainage observations, and serviceability monitoring. In this way, the proposed framework provides a structured pathway from laboratory feasibility to responsible field validation.

3.4. General Discussion

The main scientific contribution of this study is the identification and interpretation of the CBR paradox in a lateritic mine-haul-road context. The natural lateritic soil exhibited relatively favorable CBR values, but its plasticity, high fine content and water-induced disintegration behavior indicate moisture vulnerability. This does not mean that CBR is irrelevant. CBR remains a useful index for assessing penetration resistance under laboratory conditions. The limitation is that CBR alone cannot describe all mechanisms

controlling wet-season serviceability of fine-grained lateritic soils. The diagnostic concept of CBR-satisfactory but moisture-vulnerable lateritic soil therefore provides a more complete basis for engineering judgment.

Cement-polymer stabilization improved the laboratory mechanical response of the investigated soil. The stabilized mixtures developed measurable compressive strength, splitting tensile strength and elastic modulus, while the untreated soil lost integrity under soaked conditions. This supports the use of stabilization as a candidate improvement strategy. However, the role of stabilization has clear limits. The current dataset does not include permeability, capillary absorption, erosion resistance, shrinkage, wetting-drying durability, repeated-load performance or field monitoring. Therefore, the results should not be interpreted as proof of long-term water resistance or field durability.

The study also emphasizes the importance of drainage and construction control. Even if a stabilized material performs well in the laboratory, poor binder distribution, insufficient mixing depth, inadequate compaction, excessive field moisture, or poor curing may reduce field performance. Similarly, poor drainage may allow water accumulation and accelerate surface deterioration. For the Nhan Co case, where the practical problem is linked to wet-season serviceability, drainage and construction quality are not secondary considerations; they are integral to the stabilization strategy.

Field validation remains necessary because laboratory specimens cannot fully reproduce mine haul road conditions. In the laboratory, specimens are prepared and cured under controlled conditions. In the field, stabilized layers are affected by variable soil moisture, construction equipment, mixing uniformity, compaction variability, rainfall, drainage, and repeated heavy truck traffic. The proposed 200 m trial section should therefore be viewed as a future validation step, not as completed evidence. Until such a section is constructed and monitored, the present study remains a laboratory-based assessment with a proposed field validation framework.

Several limitations should be acknowledged. First, the study is based mainly on laboratory data and qualitative project-specific observations. Quantitative field monitoring data, including traffic volume, axle-load spectra, rainfall intensity, rut depth, settlement, field density, field moisture, and long-term serviceability, are not available. Second, part of the laboratory mechanical dataset has been reported previously in a study on cement-TS Mika® VN stabilized soil [18]. The novelty of the present paper therefore lies not in generating an entirely new mechanical dataset, but in reinterpreting the data within a new framework focused on moisture vulnerability, limitations of CBR-only assessment, and future field validation. Third, additional laboratory tests such as wetting-drying durability, permeability, capillary absorption, erosion resistance, shrinkage behavior and repeated-load or resilient modulus testing would strengthen the assessment. Future research should focus on implementing and monitoring the proposed trial section, with particular attention to construction quality, drainage performance, rutting, ponding, mud formation, trafficability after rainfall and maintenance demand.

4. CONCLUSIONS

This study examined the moisture vulnerability of lateritic soil used in the Nhan Co bauxite mine haul road context and proposed a laboratory-to-field framework for future validation of cement-polymer stabilization. Based on the available laboratory dataset and the proposed field-trial framework, the following conclusions can be drawn:

First, the natural lateritic soil showed relatively favorable CBR values under laboratory compaction, with CBR increasing as the degree of compaction increased.

However, this apparent bearing adequacy was contradicted by its high fine content, plasticity characteristics, and qualitative water-induced disintegration of untreated compacted specimens. This finding supports the diagnostic concept of a CBR-satisfactory but moisture-vulnerable lateritic soil, indicating that CBR alone is insufficient for evaluating lateritic materials intended for wet tropical mine haul roads.

Second, the qualitative soaking observation showed that the untreated compacted lateritic soil visibly lost integrity after short-term water exposure. Although this observation is not a standardized durability test and should not be interpreted as field validation, it provides useful laboratory evidence that the untreated soil is susceptible to water-induced disintegration. This reinforces the need to assess lateritic soils using a broader set of indicators, including Atterberg limits, fine content, compaction characteristics, soaked-condition behavior and serviceability-related concerns.

Third, cement-polymer stabilization showed laboratory-based feasibility for improving the mechanical response of the investigated lateritic soil. The stabilized mixtures developed measurable unconfined compressive strength, splitting tensile strength and elastic modulus, whereas the untreated soil lost integrity under soaked conditions. The mechanical results indicate that cement-polymer treatment can enhance the strength, tensile resistance and stiffness of the soil matrix under controlled laboratory conditions.

Fourth, the laboratory mechanical improvements should not be interpreted as field-proven performance. The actual behavior of a stabilized mine haul road depends on construction quality, binder distribution, field moisture, compaction, curing, drainage, traffic loading, rainfall exposure, and long-term maintenance conditions. Therefore, field validation remains necessary before any large-scale implementation.

Finally, a performance-based field trial framework was proposed to translate the laboratory findings into a structured future validation pathway. The framework integrates initial bearing capacity, moisture vulnerability, stabilization performance, constructability, drainage condition, construction quality control, field monitoring, and decision criteria for future scale-up. The proposed 200 m trial section should be regarded only as a future validation step, not as a completed or field-validated experiment.

The main contribution of this study is not the generation of an entirely new mechanical dataset, but the development of a diagnostic and decision-making framework for lateritic soils that may appear adequate by CBR while remaining vulnerable to moisture-induced serviceability loss in wet tropical bauxite mine haul roads.

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The field sampling and laboratory observation photographs used in this paper were taken by the authors, unless otherwise stated. Any project-specific field photographs provided by the Nhan Co plant are acknowledged accordingly in the figure captions.

Data Availability Statement:

The laboratory data supporting the findings of this study are available from the corresponding author upon reasonable request. The project-specific field trial information is based on a proposed future validation plan and does not include completed construction, monitoring, or field performance data.

Part of the laboratory mechanical dataset used in this study has been previously reported in a published study on cement-TS Mika® VN stabilized soil. In the present paper, the dataset is re-used and re-interpreted within a different analytical framework focused on moisture-vulnerability diagnosis, limitations of CBR-only assessment, and a proposed performance-based field trial framework for bauxite mine haul roads.

Declaration of Competing Interest:

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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