JURNAL TEKNIK SIPIL CENDEKIA
e-ISSN : 2723-3375
doi : **10.51988/jtsc.v7i2.562**
pp : 449-458

Case Sudy: Construction Of Soil Stabilization On Hauling Roads At A Nickel Mining Site In Souteast Sulawesi, Indonesia

[*]Tilaka Wasanta[1], Elshaan Helmmie[2], Edwin Laurencis[3]
[1,2,3] Civil Engineering, Faculty of Civil Engineering, Parahyangan Catholic University, Jl. Ciumbuleuit No. 94, Hegarmanah, Cidadap District, Bandung City, Bandung, East Java, 40141, Indonesia
[*)]Corespondent author (tilakaw@unpar.ac.id)

Received: 20 Mei 2025 Revised: 29 Mei 2026 Accepted: 29 Mei 2026

Abstract

Haul roads play an important role in supporting nickel mining operations, as their condition directly affects transportation efficiency and production performance. Inadequate road conditions can lead to reduced operational effectiveness. Thus, improving subgrade strength is necessary to ensure adequate pavement performance. This study investigated the use of cement as a soil stabilizing agent to enhance the engineering properties of haul road materials. The laboratory test results showed that the addition of 3.00% cement increased the California Bearing Ratio (CBR) from 55.87% to 168.80% after 3 days of curing. The stabilized material also achieved an Unconfined Compressive Strength (UCS) of 4.086 MPa after 28 days of curing. Pavement structural design subsequently evaluated using the Austroads (2017) method based on both laboratory test results and actual field conditions. The analysis indicated that the pavement structure could support traffic loading of up to 79.78 × 10^6 Equivalent Standard Axles (ESA) under laboratory conditions and 44.40 × 10^6 ESA under field conditions. The results demonstrate that cement stabilization can substantially improve subgrade strength and increase the structural capacity of haul road pavements, making it a viable alternative for supporting heavy mining traffic.

Keywords: *Pavement Design, Soil Stabilization, Cement, Nickel, Hauling Road*

INTRODUCTION

Indonesia possesses one of the largest nickel reserves in the world [1]. Nickel is one of the materials for various sectors, including electric vehicle battery production, stainless steel manufacturing, construction, and other industrial applications [2]. The high volume of nickel production can directly increase the intensity of haulage traffic, hence requiring haul roads to have adequate structural capacity to ensure uninterrupted daily production activities.

Road materials without specific treatment are generally weak and exhibit poor stability in accommodating high axle loads. One of the solutions to improve the structural performance of haul roads is soil stabilization [3]. The soil stabilization was first implemented in the United States in 1904 [4] by utilizing binding agents such as cement, lime, bitumen, and/or additional additives including additional modifiers, waterproofing agents, and other chemical substances [5].

Previous study in Jordan showed that mechanical compaction alone is insufficient to improve soil properties; therefore, chemical stabilization using materials such as lime or sodium silicate is recommended [6]. Soil stabilization aims to enhance soil properties such as stiffness, durability, and to reduce plasticity, thereby minimizing the potential for swelling and shrinkage [7]. In this study, the soil stabilization conducted by using 3.00%

cement content based on the density of the existing soil material. According to Gross & Adaska [8], soil–cement mixtures can improve subgrade workability, reduce plasticity, and increase bearing capacity.

The problem identified is that the existing material has been contaminated with nickel ore materials, specifically limonite and saprolite, due to spillage from dump trucks and waste material carried by truck tires. This condition increases the probability of reduced soil strength, as the mixed materials tend to be saturated and clayey in nature. Consequently, the haul road requires frequent maintenance, leading to increased delay time in hauling operations and negatively affecting daily production targets. Therefore, upgrading the haul road is necessary to accommodate continuous 24-hour hauling operations along a 9.25 km route, with an annual tonnage minimum 27.500.000 tons and axle load greater than 30 tons per axle.

Figure 1. Limonite spill on Hauling Road

Based on the condition described, this study aims to 1) evaluate the improvement of engineering properties of nickel haul road materials through cement stabilization; 2) analyze pavement performance before and after stabilization using the Austroads (2017) method, and 3) compare pavement performance predictions derived from laboratory testing and field modulus measurements to estimate the actual service life of the hauling road. The Austroads (2017) method is selected because it is capable of accounting for non-standard mining conditions and extreme loading scenarios, whereas the AASHTO 1993/2004 method has limitations in accommodating such conditions [9–11]. Specifically focuses on haul road improvement at a nickel mining operation in Southeast Sulawesi, Indonesia, where road materials have been contaminated by limonite and saprolite materials originating from nickel ore transportation activities.

Previous studies on soil stabilization have primarily focused on improvements in laboratory-based engineering properties such as California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and compaction characteristics. Study by Pongsivasathit et al. (2019) investigated the mechanical properties of cement-stabilized soils through laboratory parameters including UCS, CBR, and flexural strength [12], while Harianto et al. (2019) focused on the improvement of soil bearing capacity and strength through CBR and UCS testing of stabilized materials [13]. However, limited studies have evaluated how these improvements translate into the structural performance and service life of haul road pavements under heavy mining traffic conditions. Thompson and Visser (2007) highlighted that mine haul roads are commonly subjected to extremely high axle loads and require mechanistic structural evaluation beyond conventional empirical approaches [14]. While recent research has examined mechanistic approaches for mine haul road design, most studies focus on theoretical design procedures or comparisons with CBR-based methods rather than combining laboratory stabilization results with in-situ modulus measurements obtained after construction [15].

However, limited studies have evaluated how these improvements translate into the structural performance and service life of haul road pavements under heavy mining traffic conditions. In addition, studies integrating laboratory test results with actual field modulus measurements for mechanistic–empirical pavement analysis remain scarce, particularly for nickel mining haul roads in Indonesia.

The mechanistic–empirical approach selected because conventional empirical pavement design methods are often inadequate for mine haul roads subjected to ultra-heavy axle loads and non-standard operating conditions. Mechanistic design methods provide a more rational framework by explicitly considering pavement responses such as stresses, strains, and deflections under mining traffic loads [16].

In this study, the integration of laboratory-based cement stabilization evaluation and field-based modulus assessment. By using a Light Weight Deflectometer (LWD) within the Austroads mechanistic–empirical pavement design framework. The study also provides a comparison between predicted pavement performance under laboratory conditions and actual field conditions after construction, thereby offering a more realistic assessment of stabilized haul road performance in nickel mining operations.

METHOD

The study is conducted in Southeast Sulawesi at a nickel mining site within the region. The initial survey included test pit investigations, topographic surveys, and field CBR testing on existing subgrade materials, as well as laboratory CBR testing. Data collection carried out in September 2024, while engineering data were collected periodically before construction, during construction, and after construction until January 2026.

In the initial laboratory testing phase, the test that performed are Sieve Analysis, Atterberg Limits, Abrasion Test, and strength tests (Laboratory CBR and Unconfined Compressive Strength/UCS). Meanwhile, field testing included CBR Proving Ring measurements and Light Weight Deflectometer (LWD) tests.

This study aims to obtain a comparison of pavement performance before and after stabilization by determining the Equivalent Standard Axle (ESA) values using the Austroads (2017) method. The calculation using this method depends on variables such as soil properties and the strength of the existing subgrade, which is evaluated using a Light Weight Deflectometer (LWD).

In this study, two pavement design calculation approaches were conducted: one based on laboratory data and the other based on field data. The laboratory data used for the analysis were derived from Unconfined Compressive Strength (UCS) testing, while the field data were obtained using the Light Weight Deflectometer.

Based on these two approaches mentioned, the ESA values were determined, allowing the estimation of the actual pavement service life in accommodating hauling traffic with the planned loading conditions for the year 2026. However, it should be noted that the estimated pavement life only considers structural damage in the form of permanent deformation and does not account for actual field conditions such as weather effects, mud content, or the influence of tire friction and pressure due to haul road geometry.

Austroads 2017

Austroads is a pavement design standard used to determine an economical pavement thickness capable of delivering an acceptable level of service based on the planned traffic load. In this study, the pavement type applied is flexible pavement, and the design approach follows the mechanistic–empirical method.

According to Huang (2004) [17], mechanistic–empirical design combines mechanics-based analysis of pavement response with empirical distress models derived from field performance. This approach consists of two main components: the mechanistic component, which evaluates stresses, strains, and deflections within the pavement structure, and the empirical component, which is based on observed field performance such as rutting, fatigue cracking, deformation, and other distress modes. According to Austroads (2017), the design of flexible pavements is governed by limiting the tensile strain at the bottom of the asphalt layer and the compressive strain at the top of the subgrade. The application of the mechanistic–empirical method in this mining pavement study is justified, as it provides better adaptability to varying traffic loads, material characteristics, and environmental conditions [18].

In this study, the mechanistic–empirical analysis supported by the use of ELSYM (Elastic Layered System) software to determine tensile and compressive strain values at specific layer depths. The analysis begins by determining the axle load that produces an equivalent level of damage to the standard axle, as defined in Equation (1).

$$ESA_{ij} = \left(\frac{L_{ij}}{SL_{ij}}\right)^4$$

Where ESAij is the number of standard axle load repetitions that produce the same level of damage as a single pass of an axle group of type i carrying load Lij; SLijis the standard load for axle group type i; and Lij is the actual axle load for axle group type i. Axle groups with dual tyres and single tyres can be evaluated using Table (1) and Table (2), respectively.

Table 1. Axle Group Load That Produces an Equivalent Level of Damage to The Standard Axle

Axle Group Type	Load (kN)
Single Axle with Dual Tyres	80.00
Tandem Axle with Dual Tyres	135.00
Triaxle with Dual Tyres	182.00
Quad-axle with Dual Tyres	226.00

Table 2. Single-Tyre Axle Group Load That Produces an Equivalent Load Effect to The Standard Axle

Axle Group Type	Nominal Tyre Section Width	Load (kN)
Single Axle with Single Tyres	< 375 mm	53.00
	375 ≤ X < 450 mm	58.00
	≥ 450 mm	71.00
Tandem Axle with Single Tyres	< 375 mm	89.00
	375 ≤ X < 450 mm	98.00
	≥ 450 mm	119.00
Triaxle with Single Tyres	< 375 mm	121.00
	375 ≤ X < 450 mm	132.00
	≥ 450 mm	162.00
Quad-Axle with Single Tyres	< 375 mm	150.00
	375 ≤ X < 450 mm	164.00
	≥ 450 mm	201.00

Next, the calculations were performed to determine the tensile and compressive strains using ELSYM 5 software. These strain results were subsequently used to calculate the allowable Equivalent Standard Axle (ESA) repetitions prior to the occurrence of permanent deformation, as expressed in Equation (2).

$$N_d = \left[\frac{9150}{\mu\varepsilon}\right]^7$$

Where Nd represents the allowable number of repetitions of a standard axle load at a given strain level before permanent deformation occurs on the pavement surface, and με denotes the vertical compressive strain (microstrain) induced by the standard axle at the top of the subgrade layer.

Light Weight Deflectometer

In this study, field testing conducted using a Light Weight Deflectometer, as shown in Figure 2.

Figure 2. Light Weight Deflectometer Test

Based on the data obtained using the Light Weight Deflectometer, the results are presented in Table 3.

Tabel 3. Light Weight Deflectomter Modulus Elasticity

Modulus Elasticity			
No.	**LWD**	**No.**	**LWD**
1	402.70	18	606.60
2	402.70	19	617.20
3	438.20	20	638.30
4	450.10	21	656.30
5	493.70	22	664.90
6	495.10	23	687.50
7	499.80	24	688.40
8	520.70	25	693.90
9	526.20	26	707.20
10	539.30	27	708.60
11	557.90	28	727.50
12	558.20	29	736.30
13	567.60	30	738.10
14	571.80	31	738.70
15	572.30	32	759.40
16	585.70	33	762.30
17	604.50	34	769.30
		35	813.50

Based on Table 3, the average modulus of elasticity is 614.30 MPa. For the design calculations in this study, the design modulus taken at the 10th percentile of the measured data distribution, resulting in a value of 470.23 MPa.

RESULTS AND DISCUSSION

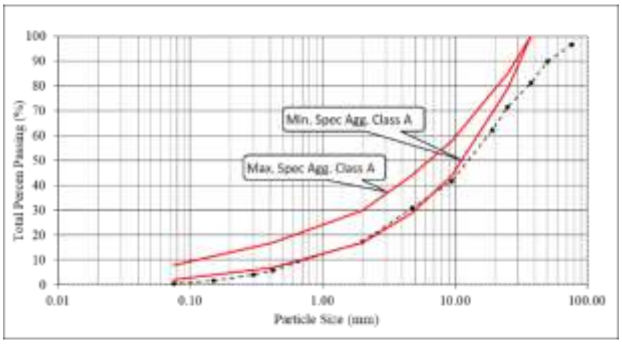
Soil Property Analysis consist the following test:

1. Sieve Analysis (SNI ASTM C136:2012)
   Based on the results of existing material sampling in the field, the sieve analysis curve is presented in Figure 3, and the corresponding data are summarized in Table 4.

Tabel 4. Sieve Analysis Existing Material

Sieve Size inch	Sieve Size mm	Retained (gr) 1	Retained (gr) 2	% Retained 1	% Retained 2	% Passing 1	% Passing 2	Average % Passing
3 "	76.20	563	-	6.57	-	93.43	100.00	96.71
2 "	50.00	1,153	769	13.46	6.65	86.54	93.35	89.95
1 1/2 "	37.50	1,850	1,804	21.59	15.61	78.41	84.39	81.40
1 "	25.00	2,765	2,833	32.27	24.51	67.73	75.49	71.61
3/4 "	19.10	3,561	3,945	41.56	34.14	58.44	65.86	62.15
3/8 "	9.50	5,363	6,206	62.59	53.70	37.41	46.30	41.86
# 4	4.75	6,335.0	7,408.0	73.93	64.10	26.07	35.90	30.99
# 10	2.00	7,386.0	9,146.0	86.19	79.14	13.81	20.86	17.33
# 40	0.42	8,196.0	10,738.0	95.65	92.91	4.35	7.09	5.72
# 50	0.30	8,298.0	10,960.0	96.84	94.83	3.16	5.17	4.16
# 100	0.15	8,454.0	11,322.0	98.66	97.97	1.34	2.03	1.69
# 200	0.075	8,528.0	11,513.0	99.52	99.62	0.48	0.38	0.43
TOTAL		**8,569.0**	**11,557.0**					
NOTE :		**CA =**	**69.01**	%	**FA=**	**30.99**	%	

Figure 2. Sieve Analysis Curve



2. Soil Properties
   Based on laboratory testing of soil properties, the test results are presented in Table 5.

Tabel 5. Soil Properties Test

Description	Value
Specific Gravity (SNI 1964:2008)	2.643
Absorption (SNI 1969:2016)	55.00%
Abrasion (SNI 2417:2008)	31.04%
Liquid Limit (SNI 1967:2008)	35.45%
Plastic Limit (SNI 1967:2008)	25.58%
Plasticity Index (SNI 1967:2008)	9.87%
Maximum Dry Density (gr/cm^3) (SNI 1743:2008)	2.130
Optimum Moisture Content (SNI 1743:2008)	7.30%

3. CBR Laboratorium (SNI 1744:2012) & UCS (Austroad 2017)
   For each cement content, three replicate specimens were prepared and tested for CBR and UCS evaluation. The reported values represent the average of the test results. Based on the laboratory California Bearing Ratio (CBR) testing results, the CBR values are presented in Table 6.

Tabel 6. CBR Value Existing Soil

Typical Method	0.1”	0.2”
15 Blow x 5 Layers	21,66%	27,62%
35 Blow x 5 Layers	41,43%	50,84%
65 Blow x 5 Layers	48,96%	55,87%

CBR testing is conducted on materials stabilized with cement using three mix proportions of 3.00%, 4.00%, and 5.00%, based on the Maximum Dry Density results presented in Table 4. Three specimens were prepared for each cement content and cured for three days prior to testing in accordance with the applicable standard. The reported CBR values represent the average of the three test results for each mixture. The resulting CBR values for these mixtures are shown in Table 7.

Tabel 7. CBR Mixing Cement

Description	Cement Content 3% 0,1"	3% 0,2"	4% 0,1"	4% 0,2"	5% 0,1"	5% 0,2"
Cement & Chemical (0,25 lt/m^2) Unsoaked 2 Days Curring	130.12	147.70	151.22	173.49	175.83	196.93
Cement & Chemical (0,25 lt/m^2) Unsoaked 3 Days Curring	140.67	168.80	168.80	194.59	193.42	236.79
Cement & Chemical (0,50 lt/m^2) Unsoaked 3 Days Curring	128.36	150.04	149.46	158.25	165.28	180.52
Cement & Chemical (0,50 lt/m^2) Soaked 3 Days Curring	223.31	263.75	283.09	320.02	328.81	358.70

Subsequently, Unconfined Compressive Strength (UCS) testing conducted on three samples with each cement contents ranging from 3.00% to 7.00%. Table 8 presents the UCS test results for cement contents between 3.00% and 7.00%. The result of UCS test shown in Table 8.

Tabel 8. UCS Test Results

Description	Cement Content				
	3.00%	4.00%	5.00%	6.00%	7.00%
UCS (MPa)	1.61	2.37	2.97	3.52	4.22

Note:
- *UCS Test based on 7-day curing time*

Based on the Unconfined Compressive Strength (UCS) results at 7 days of curing, a cement content of 3.00% is selected for the hauling road upgrading project, considering that both the CBR and UCS values have exceeded the quality requirements specified in the contract. Therefore, further increases in cement content were considered unnecessary from a technical perspective. The selected dosage also regarded as the most economical alternative because it minimized cement consumption while still providing adequate structural performance for the hauling road application.

The UCS testing then continued with samples cured for 28 days to determine the modulus of elasticity using Equation (3).

$$E_{flex} = k_{ucs} \times UCS$$

Where Eflex is the flexural modulus (MPa), UCS is the Unconfined Compressive Strength (UCS) value obtained from samples with 28 days of curing, and kucs is a constant ranging from 1.150 to 1.400 for cement-treated materials.

Pavement Design

In this study, the pavement design calculations are divided into two (2) conditions as follows:

1. Calculation using a cement content of 3.00% for an annual hauling production of 27,500,000 tons/year.
2. Back-calculation to determine the actual pavement service life using the modulus of elasticity obtained from the Light Weight Deflectometer after the hauling road upgrading.

The pavement structure data used in the analysis are presented in Table 9.

Tabel 9. Mechanical Data on Road Pavements

Unit Hauling	***Dump Truck* 6 x 4 - *Dump Truck* 8 x 4 - ADT**
Annual Production (Ton)	**27,500,000.00**
AADT	
Dump Truck 6 x 4	1,131.00
Dump Truck 8 x 4	848.00
Articulated Cump Truck	95.00
CBR Subgrade (Assumed)	6.00%
Modulus Subgrade (MPa)	60.00
Modulus Elastisitas	
Pre - Cracking (MPa)	4,698.90
Post - Cracking (MPa)	939.78

The calculation carried out by determining the proportion of vehicle axle loads. In this study, the proportions were established based on the planned or estimated operational data, as presented in Table 10 for Case 1 and Table 11 for Case 2.

Tabel 10. Axle Weight and AADT Ratios for Case 1

DT 6 x 4	**45.00 Ton**		
Axle	**Weigth Proportion**	**Weight (Ton)**	**Traffic Volume**
SAST	30.00%	13.50	1,110.00
TADT	70.00%	31.50	1,110.00

DT 8 x 4	**70.00 Ton**		
Axle	**Weigth Proportion**	**Weight (Ton)**	**Traffic Volume**
TAST	40.00%	28.00	833.00
TADT	60.00%	42.00	833.00

ADT	**80.00 Ton**		
Axle	**Weigth Proportion**	**Weight (Ton)**	**Traffic Volume**
SAST	33.81%	27.05	93.00
TAST	66.19%	52.95	93.00

Unit Hauling	***Dump Truck* 6 x 4 – *Dump Truck* 8 x 4 - ADT**
Year	**2026**

Dump Truck 6 x 4	136.00
Dump Truck 8 x 4	771.00
Articulated Cump Truck	90.00
CBR Subgrade (Assumed)	6.00%
Modulus Subgrade (MPa)	60.00
Modulus Elastisitas	
Post - Cracking (MPa)	470.23

Tabel 11. Axle Weight and AADT Ratios for Case 2

Unit Hauling	***Dump Truck* 6 x 4 - *Dump Truck* 8 x 4 - ADT**
Year	**2026**
Dump Truck 6 x 4	136.00
Dump Truck 8 x 4	771.00
Articulated Cump Truck	90.00
CBR Subgrade (Assumed)	6.00%
Modulus Subgrade (MPa)	60.00
Modulus Elastisitas	
Post - Cracking (MPa)	470.23

The calculation then continued by determining the pavement thickness to be constructed. In this study, the planned pavement thickness is 40 cm. The construction method adopted is mix-in-situ, meaning that the cement is blended directly into the existing roadway using a cement spreader and a milling machine. Based on this approach, the pavement layer configurations are presented in Table 12 for Case 1 and Table 13 for Case 2.

Tabel 12. Pavement Layer Case 1

Layer	Thickness (cm)	Thickness (Inch)	Pre-Cracking		Post-Cracking	
			E (Mpa)	E (Psi)	E (Mpa)	E (Psi)
Soil Stab Layer 1A	10.00	3.94	4,698.90	681,519.06	939.78	136,303.81
Soil Stab Layer 1B	10.00	3.94	1,579.56	229,095.61	472.40	68,515.57
Soil Stab Layer 1C	10.00	3.94	530.97	77,011.49	237.46	34,440.59
Soil Stab Layer 1D	10.00	3.94	178.49	25,887.75	119.36	17,312.18
Subgrade	-	-	60.00	8,702.28	60.00	8,702.28

Tabel 13. Pavement Layer Case 2

Layer	**Thickness (cm)**	**Thickness (Inch)**	**Post - Cracking**	
			E (Mpa)	**E (Psi)**
Soil Stab Layer 1A	10.00	3.94	470.23	68,201.22
Soil Stab Layer 1B	10.00	3.94	281.04	40,761.71
Soil Stab Layer 1C	10.00	3.94	167.97	24,361.98
Soil Stab Layer 1D	10.00	3.94	100.39	14,560.38
Subgrade	-	-	60.00	8,702.28

The difference between Table 12 and Table 13 lies in the material strength. In Table 12, the modulus of elasticity is derived from Unconfined Compressive Strength (UCS) calculations, whereas in Table 13 it is based on field measurements using a Light Weight Deflectometer.

In addition, Table 12 includes two conditions, namely pre-cracking and post-cracking. Stabilized pavement layers are expected to develop cracks over time under traffic loading, leading to a reduction in the modulus of elasticity. In contrast, the modulus values in Table 13 are assumed to represent post-cracking conditions, considering that the road has been in operation for more than three days.

Based on the data in Table 12 and Table 13, the analysis is further carried out using ELSYM5 to obtain tensile and compressive stresses at specific pavement layers, as presented in Table 14 for Case 1 and Table 15 for Case 2.

Tabel 14. Tensile and Compressive Strain Case 1

Depth Layer (inch)	Strain	Microstrain	Remarks		
		Strain			
15.74	0.0001942	194.20	Horizontal - CM	Pre - Cracking	Dual Tyres
15.74	0.0003237	323.70	Horizontal - CM	Post - Cracking	
15.77	0.0003858	385.80	Vertical - Subgrade	Pre - Cracking	
15.77	0.0006285	628.50	Vertical - Subgrade	Post - Cracking	

Depth Layer (inch)	Strain	Microstrain	Remarks		
		Strain			
15.74	0.0001385	138.50	Horizontal - CM	Pre - Cracking	Single Tyres
15.74	0.0002452	245.20	Horizontal - CM	Post - Cracking	
15.77	0.0003044	304.40	Vertical - Subgrade	Pre - Cracking	
15.77	0.0005441	544.10	Vertical - Subgrade	Post - Cracking	

Tabel 15. Tensile and Compressive Strain Case 2

Depth Layer	Strain	Microstrain	Remarks		
		Strain			
15.74	0.0002965	296.50	Horizontal - CM	Post - Cracking	Single Tyres
15.77	0.000666	666.00	Vertical - Subgrade	Post - Cracking	

Depth Layer	Strain	Microstrain	Remarks		
		Strain			
15.74	0.0003829	382.90	Horizontal - CM	Post - Cracking	Dual Tyres
15.77	0.0007395	739.50	Vertical - Subgrade	Post - Cracking	

Based on Table 14 and Table 15, the allowable number of load repetitions then determined using Equation (2), in accordance with the conditions defined for each case. Table 16 presents the allowable repetitions for Case 1, while Table 17 presents the allowable repetitions for Case 2.

Tabel 16. Allowable Repetition Case 1 (Permanent Deformation)

Dual Tyres

Description	Value	Unit
Allowable Repetition (Nd) Pre - Cracking	4,220,968,346.16	ESA
	4,220.97	x 10^6 ESA

Description	Value	Unit
Allowable Repetition (Nd) Post - Cracking	138,615,145.23	ESA
	138.62	x 10^6 ESA

Single Tyre

Description	Value	Unit
Allowable Repetition (Nd) Pre - Cracking	22,173,544,499.22	ESA
	22,173.54	x 10^6 ESA

Description	Value	Unit
Allowable Repetition (Nd) Post - Cracking	380,361,522.51	ESA
	380.36	x 10^6 ESA

Tabel 17. Allowable Repetition Case 2 (Permanent Deformation)

Dual Tyres

Description	Value	Unit
Allowable Repetition (Nd)	44,399,738.28	ESA
Post - Cracking	44.40	x 10^6 ESA

Single Tyre

Description	Value	Unit
Allowable Repetition (Nd)	92,390,656.75	ESA
Post - Cracking	92.39	x 10^6 ESA

In this study, since cement is used as the stabilization material, the pavement resistance to cracking must be evaluated. However, according to Austroads (2017), the fatigue cracking performance of a pavement can only be assessed if the following criteria are satisfied:

1. Cement content between 3.00% and 5.00%,
2. Design flexural strength of 1.0–1.5 MPa,
3. Modulus in the range of 3,000–5,000 MPa.

In Case 2, the obtained modulus falls below this specified range; therefore, fatigue cracking performance cannot be evaluated for this case. The fatigue cracking analysis for Case 1 is presented in Table 18.

Tabel 18. Fatigue Allowable Repetition

Axle Group	Expected Repetition	Critical Strain	Allowable Repetition	Damage
SAST	21,745,302.06	345.96	0.00	>100%

Axle Group	Expected Repetition	Critical Strain	Allowable Repetition	Damage
TADT	16,318,771.73	237.69	0.12	>100%
TADT	21,745,302.06	267.40	0.03	>100%
TADT	16,318,771.73	356.53	0.00	>100%

CONCLUSION

This study evaluated the effectiveness of cement stabilization for improving haul road performance at a nickel mining site in Southeast Sulawesi, Indonesia. Laboratory testing showed that the addition of 3% cement increased the CBR value from 55.87% to 168.80% and produced a 28-day UCS value of 4.086 MPa, indicating a substantial improvement in subgrade strength.

Mechanistic–empirical pavement analysis using the Austroads (2017) method demonstrated that the stabilized pavement structure could accommodate approximately 79.78×10^6 ESA under laboratory-based conditions and 44.40×10^6 ESA under actual field conditions. The lower field performance associated with reduced in-situ modulus values obtained from LWD testing.

The results confirm that cement stabilization is an effective method for enhancing the structural capacity of haul roads subjected to heavy nickel mining traffic. However, actual pavement service life remains influenced by operational factors such as drainage conditions, moisture accumulation, and maintenance practices.

Recommended for the future haul road management incorporate routine modulus monitoring using LWD or FWD equipment, improved drainage systems, and maintenance procedures that minimize disturbance of the stabilized layer. Further studies should also investigate the long-term field performance of cement-stabilized haul roads under varying environmental and traffic conditions.

DAFTAR PUSTAKA

[1] International Energy Agency. *The Role of Critical Minerals in Clean Energy Transitions*. Paris, France: IEA, 2022.

[2] International Energy Agency. *Global Supply Chains of EV Batteries*. Paris, France: IEA, 2022.

[3] Ingles, O. G. and Metcalf, J. B. *Soil Stabilisation: Principles and Practice*. Melbourne, Australia: Butterworths, 1972.

[4] Firoozi, A. A., Olgun, C. G. Firoozi, A. A., and M. S. Baghini. *Fundamentals of Soil Stabilization*. International Journal of Geo-Engineering, 8 (26): 1–16, 2017. doi:10.1186/s40703-017-0064-9.

[5] Aytekin, M. and NAS, E., *Soil Stabilisation with Cement and Lime*. Crowthorne, UK: Transport Research Laboratory, 1993.

[6] Terrel, R. L., Epps, J. A., Barenberg, E. J., Mitchell, J. K., and Thompson, M. R. *Soil Stabilization in Pavement Structures: A User's Manual Volume 1*. Washington, DC: FHWA, 1979.

[7] Milburn, J. P. and Parsons, R. L. *Performance of Soil Stabilization Agents: Final Report*. Kansas Department of Transportation, Report KU-01-8, 2004.

[8] W. S. Adaska and F. A. Gross, *Guide to Cement-Stabilized Subgrade Soils, PCA Special Report SR1007P*. Washington, DC, USA: Portland Cement Association and National Concrete Pavement Technology Center, Iowa State University, May 2020.

[9] AASHTO, *Guide for Design of Pavement Structures*. Washington DC: AASHTO, 1993.

[10] AASHTO, *Mechanistic-Empirical Pavement Design Guide*. Washington DC: AASHTO, 2004.

[11] Austroads, *Guide to Pavement Technology Part 2: Pavement Structural Design*. Sydney: Austroads, 2017.

[12] Pongsivasathit, S., Horpibulsuk, S., and Piyaphipat, S., *Assessment of Mechanical Properties of Cement Stabilized Soils*. Case Studies in Construction Materials, Vol. 11, 2019

[13] Harianto, T., Sitepu, F., and Jasruddin, *Strength Improvement of Cement Stabilized Soil by Binder Mineral Additive*, IOP Conference Series: Earth and Environmental Science, Vol. 419, 2020.

[14] R. J. Thompson and A. T. Visser. *A Mechanistic Structural Design Procedure*

For Surface Mine Haul Roads. International Journal of Surface Mining, Reclamation and Environment, 11 (3): 121–128, 1997.

[15] Ercins, S. and Bostancıoğlu, M., *Investigation of the Sufficiency of CBR Method Sections Used in the Design of Mine Haul Roads with the Mechanistic Method*, Journal of Construction, Vol. 24, No. 1, 2024, pp. 75–89.

[16] Austroads, *Guide to Pavement Technology Part 2: Pavement Structural Design*. Sydney: Austroads, 2017.

[17] Huang, Y. H. *Pavement Analysis and Design*, 2nd edition. Upper Saddle River, NJ: Pearson Prentice Hall, 2004.

[18] Austroads, *Guide to Pavement Technology Part 4D: Stabilised Materials*, Edition 2.1. Sydney, Australia: Austroads, 2019.