Engineering and Technology Journal e-ISSN: 2456-3358
Volume 11 Issue 07 July-2026, Page No.-10957-10964
DOI: 10.47191/etj/v11i07.19, I.F. – 8.595

Utilization of Mine Tailings as an Alternative Material for the Upper Foundation Layer (UFL) of Road Pavement

Eko Suprimai Danaputra[1], Novita Pradani[2], Arief Setiawan[3]
[1,2,3]Master's Program in Civil Engineering, Universitas Tadulako, Palu City, Indonesia

ABSTRACT: Tailings waste is a by-product of gold ore processing activities that is generated in large quantities and has the potential to cause environmental problems if not utilized. This study aims to evaluate the technical feasibility of tailings as an alternative material for the Upper Foundation Layer (UFL) of road pavement and to determine the percentage of tailings that can be added to the mixture to meet the technical specifications of the Upper Foundation Layer (UFL). The research was conducted experimentally in a laboratory using aggregates obtained from PT. Passokorang and tailings waste from PT. Citra Palu Minerals. Tailings contents of 0%, 25%, 50%, 75%, and 100% were used as substitutes for conventional filler. The tests conducted included sieve analysis, specific gravity and absorption, abrasion, clay content, plasticity index, modified compaction, California Bearing Ratio (CBR), Scanning Electron Microscopy (SEM), and X-Ray Fluorescence (XRF). The results showed that the tailings met the filler requirement based on the percentage passing the No. 200 sieve of 81.92%; however, they did not satisfy the requirements for clay content and the ratio of the percentage passing the No. 200 sieve to the No. 40 sieve. The compaction test results indicated that the optimum mixture occurred at a tailings content of 50%, with an optimum moisture content of 5.38% and a maximum dry density of 2.766 g/cm³. The highest CBR values were also obtained at a tailings content of 50%, reaching 75.939% in the oaked condition and 75.376% in the soaked condition. SEM analysis showed that the mixture containing 50% tailings had the highest particle density and the smallest pore area, while XRF results indicated that silicon (Si) was the dominant element at 41.356%. Although the 50% tailings mixture exhibited relatively better characteristics, none of the tailings variations tested met the minimum CBR requirement of 90% for UFL. Therefore, technically, tailings are not yet suitable for use as an alternative filler material in the Upper Foundation Layer of road pavement.

KEYWORDS: California Bearing Ratio (CBR) , SEM, Tailings Waste, Upper Foundation Layer (UFL), XRF

I. INTRODUCTION

Road infrastructure development is one of the key factors in supporting economic growth and community mobility. A good road must be able to withstand traffic loads and have a long service life with minimal maintenance (Segui et al., 2023). One of the main components that plays a significant role in the quality of road structures is the foundation layer, particularly the Upper Foundation Layer (UFL) (Fitrah, 2024).

The Upper Foundation Layer (UFL) functions as a transition layer between the lower foundation layer and the pavement surface layer (Firmansyah & Wacono, 2025). This layer plays a role in distributing traffic loads to the underlying layers, maintaining the stability of the pavement structure, and supporting resistance to environmental influences such as water and temperature changes (Jumardi et al., 2025). Therefore, the selection of materials and the technical characteristics of the UFL are critical factors in determining road quality.

Mine tailings are a by-product of gold ore processing activities, generated in large quantities and potentially causing environmental problems if not utilized (Lumentah et al., 2021). The continuous increase in mining activities has resulted in a growing volume of tailings waste. In general, tailings are stored in designated disposal areas that require extensive land and continuous management to prevent negative environmental impacts. Therefore, various studies have been conducted to utilize tailings as an alternative material in the construction sector, such as concrete mixtures, soil stabilization, and road pavement materials. The utilization of tailings in construction can not only reduce the amount of waste that must be managed but also support the concept of sustainable development through the use of industrial by-products as substitutes for natural materials, the availability of which is becoming increasingly limited (Kementerian Lingkungan Hidup dan Kehutanan, 2020).

PT. Citra Palu Minerals (CPM) is a mining company located in Poboya Village, Mantikulore District, Palu City, Central Sulawesi Province, with gold as its mining operation commodity (PT. CPM, 2025). PT. Citra Palu Minerals (CPM) began operations in 2017, with a three-year construction period, and commenced production in 2020.

In carrying out its production activities, PT. Citra Palu Minerals (CPM) generates waste materials from ore processing, known as tailings, in a considerable volume averaging 4,500 tons per day (PT. CPM, 2025). Given such a large volume, it is unfortunate if this waste is not utilized in construction works. Therefore, the author conducted a study on the utilization of mine tailings as an alternative material for the Upper Foundation Layer (UFL) of road pavement.

Based on the above description, the objective of this study is to determine the technical feasibility of tailings as an alternative material for the Upper Foundation Layer (UFL) of road pavement and to identify the percentage of tailings that can be added to the mixture in order to meet the technical specifications of the Upper Foundation Layer (UFL) for road pavement. This study is expected to demonstrate that the use of tailings as a substitute filler material in the Upper Foundation Layer (UFL) of road pavement can serve as an alternative material solution when commonly used materials become scarce.

II. MATERIALS AND METHODS

A. *Research Design*

This study is a laboratory experimental study aimed at analyzing the effect of using tailings from gold ore processing as a filler material on the characteristics of the Upper Foundation Layer (UFL). The study began with testing the physical properties of aggregates and tailings, including sieve analysis, specific gravity and absorption, abrasion, plasticity index, clay content, and aggregate particle fracture. Subsequently, UFL mixtures were designed with tailings contents of 0%, 25%, 50%, 75%, and 100% as substitutes for conventional filler. The performance of the mixtures was evaluated through compaction tests to determine the optimum moisture content and maximum dry density, as well as California Bearing Ratio (CBR) tests to determine the bearing capacity of the mixtures. In addition, the microstructural characteristics and chemical composition of the tailings were analyzed using Scanning Electron Microscopy (SEM) and X-Ray Fluorescence (XRF). The test results were then analyzed to determine the effect of variations in tailings content on the characteristics of the UFL and to obtain the optimum tailings content that meets the technical specifications. The study was conducted at the Soil Mechanics Laboratory, the Concrete and Materials Laboratory of the Faculty of Engineering, and the Integrated Laboratory of Tadulako University, Palu.

B. Research Materials

The materials used in this study consisted of coarse and fine aggregates obtained from the stone crusher plant of PT. Passokorang, located in Watusampu Village, Ulujadi District, Palu City, and filler material obtained from tailings generated by the gold ore processing activities of PT. Citra Palu Minerals, located in Poboya Village, Mantikulore District, Palu City.

C. Material Testing

The aggregate testing methods used in this study were based on the procedures issued by the Directorate General of Highways, Ministry of Public Works of the Republic of Indonesia, as well as the Indonesian National Standards (SNI) testing methods (Direkrorat Jendral Bina Marga, 2020). The testing methods included sieve analysis, specific gravity and water absorption testing, abrasion testing, plasticity index testing, clay content testing, and coarse aggregate fractured particle testing.

D. Upper Foundation Layer (UFL) Mix Design

The method used to determine the mixture composition that complies with the technical specifications for the Upper Foundation Layer (UFL) mix design was the compaction method and California Bearing Ratio (CBR) testing (Basri et al., 2024). This method was carried out through a trial-and-error approach, followed by comparing the results with the established technical specifications.

E. Determination of Optimum Moisture Content (OMC)

In this study, five moisture content variations were applied to five test specimens, namely 3%, 4%, 5%, 6%, and 7%. In addition, five tailings content variations were used for five test specimens, namely 0%, 25%, 50%, 75%, and 100%. For each variation of moisture content and tailings content, one test specimen was prepared for compaction testing and one test specimen for CBR testing. Accordingly, a total of 25 test specimens were prepared for compaction testing and 50 test specimens for CBR testing, resulting in an overall total of 75 test specimens for this study.

F. Compaction Testing

Compaction serves to increase the bearing capacity of the soil; as the bearing capacity increases, deformation can be prevented (Irianto et al., 2023). This test is intended to determine the maximum dry unit weight or maximum dry density (γd max) and the optimum moisture content (ω opt). There are two types of laboratory compaction tests that can be used to determine the optimum moisture content and maximum dry density, namely Standard Compaction and Modified Compaction (Adenora, 2021). In this study, the Modified Compaction method was used.

G. California Bearing Ratio (CBR) Testing

The California Bearing Ratio (CBR) test is used to evaluate the potential strength of subgrade, subbase, and base course materials, including recycled materials used for road and airfield pavements (Alif et al., 2025). The unsoaked California Bearing Ratio (CBR) test was conducted in accordance with the method specified in SNI 1744:2012 (Badan Standardisasi Nasional, 2012). In this study, the CBR test was carried out under two conditions: soaked and unsoaked.

H. *Scanning Electron Microscopy (SEM)* Testing

This test was conducted to provide information on the microstructure of gold mine waste (tailings). The equipment used for Scanning Electron Microscopy (SEM) testing consisted of one complete SEM unit with four components:

an electron gun, a lens system, a scanning system, and a detection system (Goldstein et al., 2003) (Masta, 2020).

I. *X-Ray Fluorescence (XRF) Testing*

This test was conducted to provide information on the chemical element composition of gold mine waste (tailings). The equipment used for X-Ray Fluorescence (XRF) testing was a spectrometer equipped with several components, namely an X-ray source, detector, sample chamber, collimator, X-ray filter, and computer system (Sclotz & Uhlig, 2006) (Admojo, 2020).

J. Research Analysis

All tests conducted, ranging from sieve analysis to CBR, SEM, and XRF testing in the laboratory, produced data that were subsequently analyzed to generate comparative graphs illustrating the effect of tailings as an alternative filler material on the characteristics of the Upper Foundation Layer (UFL). These included graphs showing the relationship between the content of tailings as an alternative filler and the maximum dry density value, as well as the CBR value, in addition to analyses of the SEM and XRF test results. However, before the aggregates were varied with tailings as an alternative filler material, physical property tests were first conducted on the material with 0% alternative filler content, including sieve analysis, specific gravity and absorption, abrasion, and Atterberg limits. The data obtained served as a basis for comparison between the material condition with 0% alternative filler content and the material that had been modified with the alternative filler.

III.RESULT AND DISCUSSION

A. Results of Aggregate Physical Characteristics Testing

1. Sieve Analysis Test Results

In this test, sieve analysis was conducted on only two aggregate fractions, namely the stone dust fraction and the tailings waste fraction. The test results obtained are presented as follows:

Table 1. Sieve Analysis Test Results of the Stone Dust Fraction

Sieve No.	Opening (mm)	Weight Retained (g)	Cumulative Retained (g)	% Retained	% Passing
-	-	-	-	-	100.00
#3/8"	9.500	2.9	2.91	0.19	99.81
#4	4.750	5.8	8.73	0.58	99.42
#8	2.360	531.3	540.03	36.00	64.00
#20	0.850	544.5	1084.51	72.30	27.70
#40	0.425	188.0	1272.53	84.84	15.16
#60	0.250	100.9	1373.46	91.56	8.44
#80	0.180	54.8	1428.29	95.22	4.78
#100	0.150	27.9	1456.19	97.08	2.92
#200	0.075	17.6	1473.83	98.26	1.74
Pan	-	26.2	1500.00	100.00	0.00

Table 2. Sieve Analysis Test Results of the Tailings Fraction

Sieve No.	Opening (mm)	Weight Retained (g)	Cumulative Retained (g)	% Retained	% Passing
-	-	-	-	-	100.00
#3/8"	9.500	0.0	0.00	0.00	100.00
#4	4.750	15.1	15.12	1.01	98.99
#8	2.360	26.5	41.66	2.78	97.22
#20	0.850	54.7	96.31	6.42	93.58
#40	0.425	61.1	157.43	10.50	89.50
#60	0.250	26.1	183.52	12.23	87.77
#80	0.180	49.9	233.37	15.56	84.44
#100	0.150	22.3	255.64	17.04	82.96
#200	0.075	15.6	271.21	18.08	81.92
Pan	-	1228.8	1500.00	100.00	0.00

Based on the results of the sieve analysis test, it can be determined that the tailings waste meets the requirements as a filler material for the Upper Foundation Layer (UFL) mixture because the percentage passing the No. 200 sieve is 81.92%, while the technical specification requires a minimum of 75% passing the No. 200 sieve.

The requirement for the ratio of the percentage passing the No. 200 sieve to that passing the No. 40 sieve is a maximum of 2/3. From the sieve analysis results, it can be observed that the stone dust aggregate meets this requirement, whereas the tailings waste aggregate does not. The comparison results are presented as follows:

Table 3. Comparison of the Percentage Passing the No. 200 Sieve to the No. 40 Sieve

No.	Aggregate Type	Percentage Passing Sieve (%)		Requirement	Result (6 = 3/4)	Remarks
		No. 200	No. 40			
1	Stone Dust	1.74	15.16	≤ 2/3 (0.667)	0.115	Meets the Requirement
2	Tailings Waste	81.92	89.50	≤ 2/3 (0.667)	0.915	Does Not Meet the Requirement

2. Abrasion Test Results and Specific Gravity and Absorption Test Results of Coarse Aggregate

The abrasion test was conducted in accordance with the method specified in SNI 03-1969-1990. The results obtained are presented as follows:

Table 4. Abrasion Test Results

No.	Test	Specification	Test Result	Status
1	Los Angeles Abrasion Test (500 Revolutions)	≤ 40%	22.18%	Passed

3. Fine Aggregate Specific Gravity Test Results

The fine aggregate specific gravity test was conducted in accordance with the method specified in SNI 1970:2008. The results obtained are presented as follows:

Tabel 5. Fine Aggregate Specific Gravity Test Results

No.	Test Type	Stone Dust	Tailings Waste
1	Bulk Specific Gravity	2.480	2.630

4. Coarse Aggregate Broken Grain Test Results

The coarse aggregate grain breakage test was conducted according to the method specified in SNI 7619:2012. This method regulates the implementation procedure and determination of the percentage of coarse aggregate breakage to determine the quality of coarse aggregate to be used in a construction. The use of coarse aggregate grains with broken surfaces will increase the frictional resistance between grains in the mixture, thereby increasing the stability of the mixture, and will also provide a good surface texture, thus increasing the roughness.

Table 6. Coarse Aggregate Fractured Particle Test Results

No.	Aggregate Size	Sample Weight (kg)	Sample Weight with 1 Fractured Face (kg)	Sample Weight with ≥ 2 Fractured Faces (kg)
1	1"	0.908	0.257	0.651
2	3/8"	1.550	0.226	1.324
3	No. 4	0.725	0.004	0.721
Total		**3.183**	**0.487**	**2.696**

Percentage of Fractured Coarse Aggregate Particles:

$$= \left(\frac{\text{Weight of Sample with 1 Fractured Face + Weight of Sample with ≥2 Fractured Faces}}{\text{Total Sample Weight}}\right) \times 100\%$$

$$= \left(\frac{0{,}487 \text{ Kg} + 2{,}696 \text{ Kg}}{3{,}183 \text{ Kg}}\right) \times 100\%$$

$$= 100\%$$

Based on the fractured coarse aggregate particle test results, 100% of the aggregate sample consisted of fractured particles. This result satisfies the specified technical requirement of 95/90%.

5. Clay Content Test Results

This test was conducted using the procedure specified in SNI 3423:2008. The clay content test results are presented as follows:

Table 7. Clay Content Test Results

No.	Aggregate Type	Requirement	Result	Remarks
1	Tailings Waste	0–5%	13.93%	Does Not Meet the Requirement
2	Stone Dust	0–5%	0.19%	Meets the Requirement

6. Plasticity Index Test Results

The plasticity index test was conducted in accordance with the method specified in SNI 1966:2008. The test results are presented as follows:

Table 8. Plasticity Index Test Results

No.	Aggregate Type	Atterberg Limits		Liquid Limit Requirement	Plasticity Index Requirement	Plasticity Index (7 = 3 - 4)	Remarks
		Liquid Limit	Plastic Limit				
1	Stone Dust	5.98	0.00	0–25	0–6	5.98	Meets the Requirement
2	Tailings Waste	4.59	0.00	0–25	0–6	4.59	Meets the Requirement

B. Stages of Preparing the Upper Foundation Layer (UFL) Mixture and Results of Mechanical Characteristics Testing of the Upper Foundation Layer (UFL) Mixture

1. Compaction Test Results

The compaction test was conducted in accordance with the method specified in SNI 1743:2008. The test was carried out to determine the relationship between variations in average moisture content and average dry density at tailings waste contents of 0%, 25%, 50%, 75%, and 100%. The test results can be visualized in graphical form as follows:

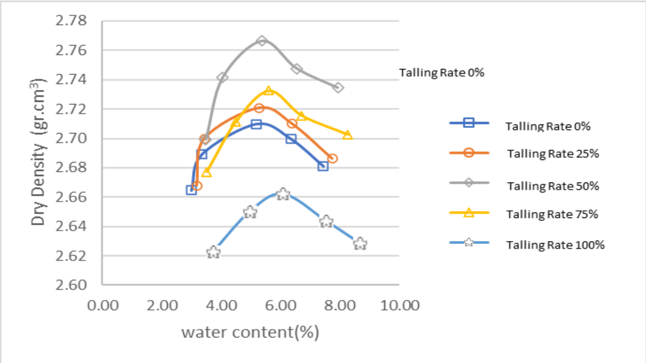


Figure 1. Relationship Between Average Moisture Content Variation and Average Dry Density at Different Tailings Waste Contents

Based on the compaction test results of the Upper Foundation Layer (UFL) mixture, the highest maximum dry density (γd max) was obtained from the mixture containing 50% tailings waste at an optimum moisture content (ω opt) of 5.38%, with a maximum dry density (γd max) value of 2.766 g/cm³. In contrast, the lowest maximum dry density (γd max) was obtained from the mixture containing 100% tailings waste at an optimum moisture content (ω opt) of 6.84%, with a maximum dry density (γd max) value of 2.643 g/cm³.

From Figure 1, Relationship Between Average Moisture Content Variation and Average Dry Density at Different Tailings Waste Contents, it can be observed that as the tailings content increases, the moisture content also increases, accompanied by a decrease in dry density. The optimum UFL mixture was achieved with a tailings content of 50%.

2. Soaked and Unsoaked California Bearing Ratio (CBR) Test Results

The unsoaked California Bearing Ratio (CBR) test was conducted in accordance with the method specified in SNI 1744:2012. The results showing the relationship between variations in average moisture content and the average soaked and unsoaked CBR values at tailings waste contents of 0%, 25%, 50%, 75%, and 100% can be presented in the form of tables and graphs as follows:

Table 9. Optimum Moisture Content, Maximum Dry Density, Unsoaked CBR, and Soaked CBR Values at Different Tailings Content Variations

Tailings Content Variation (%)	Optimum Moisture Content (%)	Maximum Dry Density (g/cm³)	Unsoaked CBR Value (%)	Soaked CBR Value (%)
0	5.19	2.71	72.305	71.741
25	5.28	2.72	73.371	72.807
50	5.38	2.77	75.939	75.376
75	5.60	2.73	74.436	73.872
100	6.08	2.66	70.927	70.363

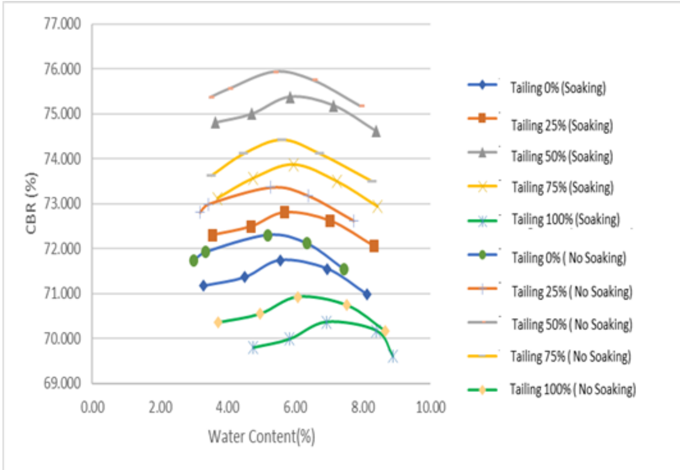


Figure 2. Graph of the Relationship between Variations in Average Water Content with Average Unsoaked CBR Values and Average Soaked CBR at Tailings Waste Contents of 0%, 25%, 50%, 75%, and 100%

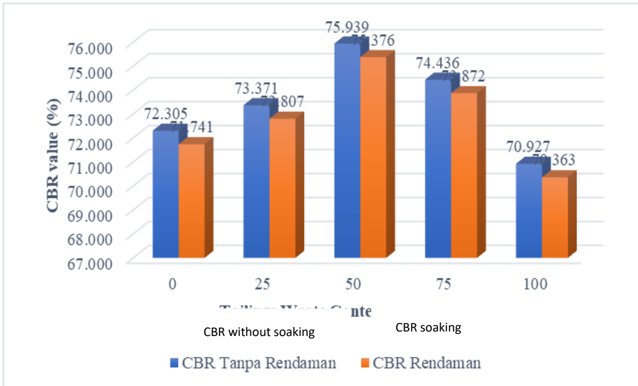


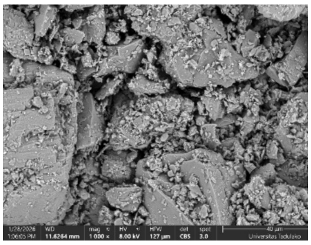
Figure 3. Relationship Between Tailings Waste Content Variation and the Highest Soaked CBR and Unsoaked CBR Values

Based on the results obtained, the Unsoaked CBR values were higher than the Soaked CBR values for each variation of tailings waste content.

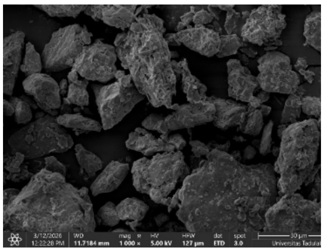
The minimum required Soaked California Bearing Ratio (CBR) value for an Upper Foundation Layer (UFL) mixture is 90%. Based on the soaked CBR test results, the highest CBR value obtained was 75.376%. Therefore, it can be concluded that the mixture does not meet the requirements for use as an Upper Foundation Layer (UFL) in road pavement.

C. *Scanning Electron Microscopy* (SEM) Test Results

Prior to the SEM test, samples of stone dust aggregate, tailings waste, and fine aggregate mixtures of the Upper Foundation Layer (UFL) with tailings waste contents of 0%, 50%, and 100% were prepared in a dry condition. The SEM test results are presented as follows:



a. Tailings Waste

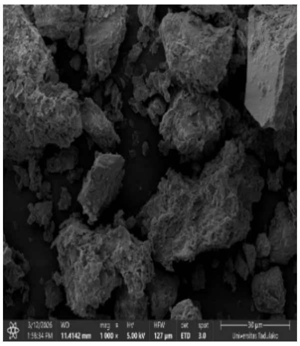


b. Stone Dust Aggregate

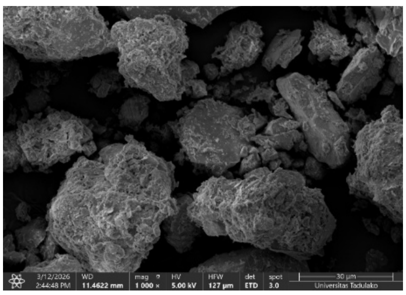
Figure 4. SEM Test Results of Tailings Waste and Stone Dust Aggregate at 1000× Magnification

SEM observations at 1000× magnification showed that both tailings waste and stone dust aggregate possess irregular (angular) particle characteristics, indicating mechanical formation. The tailings particles were dominated by fine fractions (<50 µm) with a smooth surface texture and a pore area of 2,253.93 µm² (21%), whereas the stone dust aggregate exhibited a rougher surface texture with a pore area of 2,307.59 µm² (21.50%). The dense particle arrangement, together with the irregular and angular particle shapes, has the potential to enhance interlocking interactions among particles and with binding materials, thereby influencing the compaction, permeability, and bearing capacity of the material.

a. UFL Mixture (Fine Aggregate) with 0% Tailings Content



b. UFL Mixture (Fine Aggregate) with 50% Tailings Content



c. UFL Mixture (Fine Aggregate) with 100% Tailings Content

Figure 5. SEM Test Results of UFL Mixtures (Fine Aggregate) with Tailings Content Variations of 0%, 50%, and 100% at 1000× Magnification

SEM images of the UFL mixtures (fine aggregate) with tailings content variations of 0%, 50%, and 100% at 1000× magnification showed that all mixtures consisted of densely packed particles with irregular (angular) shapes. At 0% tailings content, the mixture was dominated by the characteristics of stone dust, exhibiting a rough surface texture and a pore area of 2,575.92 µm² (24%). At 50% tailings content, the mixture displayed a combination of stone dust and tailings characteristics, with a rough-to-smooth texture and the smallest pore area of 2,039.27 µm² (19%). Meanwhile, at 100% tailings content, the mixture was dominated by the characteristics of tailings, exhibiting a smooth surface texture and a pore area of 2,307.59 µm² (21.50%). These results indicate that the addition of tailings affects the surface texture and pore distribution of the UFL mixture.

The comparison of the SEM test results of the UFL mixtures (fine aggregate) with tailings content variations of 0%, 50%, and 100% can be explained as follows:

The SEM analysis results provide visual and quantitative insights that support the understanding of the physical properties of the materials and serve as an important basis for evaluating material performance in construction applications.

D. X-Ray Fluorescence (XRF) Test Results of Tailings Waste

The X-Ray Fluorescence (XRF) test was conducted to identify the types and percentages of chemical elements contained in the tailings waste. This method works by directing X-rays onto the sample, causing each element to emit secondary X-rays with different energy levels, which are then analyzed by a computer to determine the elemental composition of the material. The XRF test results of the tailings waste can be visualized in the following graph:

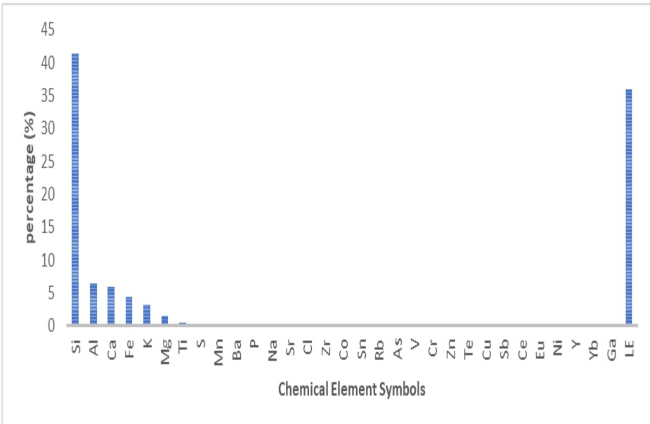


Figure 6. XRF Test Results of Gold Tailings Waste

The XRF test results showed that the tailings waste was dominated by silicon (Si) at 41.356%, followed by light elements (LE) at 35.977%, aluminum (Al) at 6.382%, calcium (Ca) at 5.907%, and iron (Fe) at 4.410%. The dominance of silicon indicates that the tailings contain a high proportion of silicate minerals, while the presence of aluminum, calcium, and iron suggests their potential contribution to the physical and mechanical properties of the material. The elemental composition indicates that the tailings waste has the potential to be utilized as an alternative filler material in Upper Foundation Layer (UFL) mixtures.

CONCLUSIONS

Based on the research results and data analysis, it can be concluded that, technically, tailings cannot be utilized as an alternative filler material in Upper Foundation Layer (UFL) mixtures because the mechanical characteristics testing showed that the highest California Bearing Ratio (CBR) value was obtained from the Unsoaked CBR test with a tailings content variation of 50%, resulting in a CBR value of 75.939%, which is lower than the minimum value of 90% specified in the technical specifications. Although, from the aggregate physical characteristics tests, only 3 (three) out of 10 (ten) types of tests did not meet the technical specifications. The aggregate physical characteristics tests that met the technical specifications were the percentage passing the No. 200 sieve, specific gravity and absorption of coarse aggregate, specific gravity of fine aggregate, percentage of fractured particles in coarse aggregate, coarse aggregate abrasion, liquid limit, and plasticity index. Meanwhile, the aggregate physical characteristics tests that did not meet the technical specifications were the ratio of the percentage passing the No. 200 sieve to the No. 40 sieve, clay content, and the product of the plasticity index and the percentage passing the No. 200 sieve.

Of the tailings waste content variations applied to the Upper Foundation Layer (UFL) mixtures, namely 0%, 25%, 50%, 75%, and 100%, none met the technical specifications required for use in the Upper Foundation Layer (UFL) of road pavement. The most optimum UFL mixture was the mixture containing 50% tailings. In addition, the XRF test results showed that the tailings waste was dominated by silicon (Si) at 41.356%, followed by light elements (LE) at 35.977%, aluminum (Al) at 6.382%, calcium (Ca) at 5.907%, and iron (Fe) at 4.410%. The dominance of silicon indicates that the tailings contain a high proportion of silicate minerals, while the presence of aluminum, calcium, and iron suggests their potential contribution to the physical and mechanical properties of the material.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to PT. Citra Palu Minerals (CPM) for granting permission and providing support during the research activities. The authors also extend their appreciation to the Civil Engineering Study Program, Faculty of Engineering, Tadulako University, for providing academic support, laboratory facilities, and assistance throughout the research process. Special thanks are addressed to the supervisors for their guidance, valuable suggestions, encouragement, and continuous support throughout the completion of this study. Their contributions have been invaluable to the successful completion of this research.

REFERENCES

1. Adenora, N. (2021). *Perbandingan Nilai Derajat Kepadatan Tanah Metode Standard Proctor Dengan Alat Uji Tekan Modifikasi Dan Uji Sand Cone Di Lapangan* [Universitas Lampung]. Fakultas Teknik
2. Admojo, Y. (2020). *Analisis Kualitas Batugamping Sebagai Bahan Baku Semen Dengan Menggunakan Metode X-Ray Diffraction (XRD) dan X-Ray Fluorescence (XRF) Pada Kawasan Indarung, Kota Padang, Provinsi Sumatra Barat)*. Universitas Islam Riau.
3. Alif, F., Rustamin, M., & Mustika, W. (2025). Inovasi Material Limbah Crusher Untuk Meningkatkan Daya Dukung Lapis Pondasi Bawah Konstruksi Jalan Berbasis Keberlanjutan. *Jurnal Media Konstruksi*, *10*(1), 60–71.
4. Badan Standardisasi Nasional. (2012). *SNI 1744:2012: Metode uji CBR laboratorium*.
5. Basri, D. R., Tisnawan, R., & Edriansyah, D. (2024). Pemanfaatan Limbah Galian Aspal Hot Mix pada Campuran Lapisan Pondasi atas terhadap Nilai California Bearing Ratio (Daya Dukung). *Impression: Jurnal Teknologi Dan Informas*, *3*(1), 23–3.
6. Direktorat Jendral Bina Marga. (2020). *Spesifikasi khusus lapis fondasi agregat menggunakan tailing (LFAT)*. Kementerian Pekerjaan Umum Republik Indonesia.
7. Firmansyah, G., & Wacono, S. (2025). Analisis pengendalian kualitas lpa dan laston untuk penyiapan badan jalan. *Seminar Nasional Teknik Sipil Politeknik Negeri Jakarta*.
8. Fitrah, W. (2024). *Perencanaan Tebal Perkerasan Lentur Pembangunan Jalan Simpang Bonjol - Batas Kabupaten Lima Puluh Kota (SULIKI) Sumatera Barat dengan Menggunakan Metode Analisa Komponen dan MDPJ 2017* [Universitas Muhammadiyah Sumatera Barat]. http://eprints.umsb.ac.id/id/eprint/2625
9. Goldstein, J., Newbury, D., Joy, D., Lyman, C., Echlin, P., & Lifshin, E. (2003). Scanning Electron Microscopy and X-Ray Microanalysis. In *Third Edition*. Plenom Publisher.
10. Irianto, Sitorus, P. H., Didik S. S. Mabui, Rochmawati, R., & Lapian, F. E. P. (2023). Analisis Pengaruh Penambahan Limbah Tailing PT . Freeport sebagai Bahan Stabilisasi Tanah pada Lapis Pondasi Jalan. *Jurnal Teoretis Dan Terapan Bidang Rekayasa Sipil*, *30*(3), 449–456. https://doi.org/10.5614/jts.2023.30.3.13
11. Jumardi, Musdalifah, & Umar, B. (2025). Analisis

Pengaruh Kerusakan Bahu Jalan Akibat Kepadatan Lapisan Pondasi Kelas. *Jurnal Mahakarya Konstruksi*, *02*(1), 92–98.

12. Kementerian Lingkungan Hidup dan Kehutanan. (2020). *Teknologi pengolahan emas pada pertambangan emas skala kecil di Indonesia (Vol. 4)*.
13. Lumentah, E., Manoppo, F. J., & Sompie, O. B. A. (2021). Analisis Kestabilan Dam Tailing PT. Sumber Energy Jaya. *Jurnal Ilmiah Media Engineering*, *11*(3), 171–178.
14. Masta, N. (2020). *Buku Materi Pembelajaran Scanning Electron Microscopy*. FKIP UKI.
15. PT. CPM. (2025). *Data produksi tailing (Dokumen internal)*.
16. Sclotz, R., & Uhlig, S. (2006). *Introduction to X-ray Fluoresence Analysis (XRF)*. Bruker AXS GmbH.
17. Segui, P., Safhi, M., Amrani, M., & Benzaazoua, M. (2023). Mining Wastes as Road Construction Material : A Review. *Minerals*, *13*(90), 1–18.