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Analysis of the Utilization of Fly Ash and Bottom Ash (FABA) Waste in Coal Haul Road Construction to Reduce Split Stone Costs in Bayung Lencir District

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Keywords:
fly ash and bottom ash (FABA); coal haul road; split stone; construction cost; California Bearing Ratio (CBR).

Abstract

Fly ash and bottom ash (FABA), byproducts of coal combustion in power plants, have potential applications as construction materials, particularly following the reclassification of certain types of FABA as nonhazardous waste under Indonesian Government Regulation No. 22 of 2021. Meanwhile, crushed stone represents a major cost component in coal haul road construction. This study aimed to identify an appropriate method for utilizing FABA in coal haul road construction at PT MAL, evaluate its application, and compare the associated crushed stone material costs. The research employed an applied, descriptive quantitative case study approach, using primary data obtained through field observations and measurements and secondary data collected from company reports, regulations, and relevant literature. Data were analyzed using Microsoft Excel. The most effective compaction configuration consisted of three layers measuring 20, 15, and 15 cm, respectively, achieving an average California Bearing Ratio (CBR) of 37.87%, with approximately 22.9 hours of compaction reported for each layer. FABA was used as the primary road embankment material, forming a layer approximately 50 cm thick, while crushed stone was applied only to the entrance and exit access roads of Pit BL2. The cost of crushed stone decreased from IDR 613,770,000 to IDR 144,909,600, representing a reduction of IDR 468,860,400 (76.39%). These findings indicated that FABA utilization could substantially reduce crushed stone material costs in coal haul road construction. However, the reported savings were limited to the crushed stone material component and did not constitute verified reductions in total construction costs.

INTRODUCTION

Fly ash and bottom ash (FABA) are byproducts of coal combustion in coal-fired power plants, with potential applications as more environmentally sustainable construction materials (Ayuningtyas et al., 2022, 2023). Growing global energy demand has sustained coal consumption across industrial sectors and electricity generation, resulting in substantial quantities of combustion residues (Anggara et al., 2021, 2024). Without appropriate management and utilization, FABA

accumulation may contribute to environmental contamination, including air, soil, and water pollution (Rashid et al., 2023). Consequently, various countries have increasingly adopted circular economy and sustainable construction approaches that incorporate FABA as an alternative material in infrastructure development, particularly road and pavement construction (Hui et al., 2025; Zimar et al., 2022). Depending on its physical and chemical characteristics, FABA can improve the mechanical performance of road foundation layers and partially replace conventional natural aggregates, thereby reducing dependence on virgin construction materials (Rochanavibhata et al., 2024; Wiranata et al., 2022).

Across Southeast Asia, particularly Indonesia, continued coal consumption has contributed to increasing volumes of FABA generated by coal-fired power plants and related industries (Putra et al., 2024). Following the enactment of Indonesian Government Regulation No. 22 of 2021, certain categories of FABA from specified sources were excluded from the hazardous and toxic waste (B3) classification, creating opportunities for broader utilization in construction and mining activities (Kementerian Energi dan Sumber Daya Mineral, 2021; Nasution et al., 2026). FABA typically contains silica and alumina, while fly ash may exhibit pozzolanic properties that support its application in soil stabilization and road construction. Depending on material characteristics and treatment methods, FABA can be incorporated into road base and subbase layers and concrete paving blocks (Abdul Halim & Sarif, 2021; Isnandar et al., 2024). These applications may contribute to resource efficiency, reduce reliance on natural aggregates, and support sustainable infrastructure development.

Previous studies in Indonesia have demonstrated the potential of FABA for road construction applications. Indriyati et al. (2019) reported that FABA used in road pavement base layers achieved California Bearing Ratio (CBR) values of up to 252%, indicating substantial bearing capacity under the reported testing conditions. Samosir et al. (2021) found that FABA mixtures incorporated into subbase layers improved bearing capacity compared with conventional materials and satisfied the applicable Bina Marga specifications. Similarly, Hilman et al. (2024) demonstrated that FABA combined with stabilizing agents, such as cement or lime, could serve as an alternative subbase material in areas with limited access to high-quality aggregates. Nevertheless, previous research has predominantly emphasized laboratory evaluations of physical and mechanical properties, including CBR, compressive strength, and soil stabilization performance (Amin et al., 2024; Firdaus et al., 2024; Marchellino & Nugraha, 2025). These investigations have provided important technical evidence but have offered limited consideration of operational conditions in coal mining, particularly the application of FABA in coal haul road construction. Furthermore, variations in reported performance indicate that the effectiveness of FABA as an aggregate substitute depends on material composition, mixture proportions, compaction conditions, and site-specific characteristics. Therefore, further field-based investigations are necessary to evaluate its technical suitability and economic implications under actual mining conditions.

In coal mining operations, haul roads constitute essential infrastructure for transporting coal from mining pits to stockpiles or loading facilities. Inadequate haul road conditions can increase

operating costs through frequent maintenance, higher fuel consumption, reduced hauling productivity, and greater occupational safety risks (Gouda et al., 2024; Terziyski & Kaykov, 2022). To maintain adequate road performance, mining companies commonly use crushed stone as a pavement or structural layer material. However, crushed stone procurement, transportation, placement, and maintenance can represent substantial construction expenditures (Samawi et al., 2024). PT MAL faces considerable demand for haul road construction materials to support its coal production and transportation activities. At the same time, the availability of FABA presents an opportunity to partially substitute conventional crushed stone with an alternative material. Evaluating the technical performance and material cost implications of FABA under actual operating conditions is therefore essential to determining its potential contribution to haul road construction efficiency. If the material satisfies the applicable engineering requirements, its utilization could reduce dependence on natural aggregates while supporting industrial byproduct recovery.

Accordingly, this study addressed three research questions: What construction method was appropriate for incorporating FABA into coal haul roads at PT MAL? How did the constructed FABA layers perform against the specified technical requirements? To what extent could FABA utilization reduce crushed stone material costs compared with conventional construction practices? The study aimed to identify an appropriate FABA construction and compaction method, evaluate its technical performance, and compare the associated crushed stone material costs. Its scope included haul road relocation and construction planning based on the 2026 mining direction, FABA and crushed stone placement configurations, and relevant performance indicators, including bearing capacity, field density, constructed layer thickness, surface stability, deformation, and road conditions before and after vehicle traffic, where data were available. The economic assessment focused on the cost implications of substituting FABA for crushed stone, while environmental impact assessment was excluded. The findings were expected to provide practical technical and economic considerations for evaluating FABA as an alternative material in coal haul road construction and contribute to resource efficiency and circular economy practices within Indonesia's coal mining industry.

METHOD

Research Location and Time

PT MAL was a privately owned Indonesian coal mining company operating under a Mining Business Permit (IUP) issued through South Sumatra Governor's Decree No. 0615/DPMPTSP.V/X/2018, valid until 2028. The company's production operation permit covered an area of 4,563 hectares in Bayung Lencir District, Musi Banyuasin Regency, South Sumatra Province (Figure 1). The mining site was characterized by geological strata comprising soil, overburden, upper coal seams, interburden, and lower coal seams. The site was selected because ongoing changes in mining operations required the relocation of coal haul roads, creating an opportunity to evaluate alternative construction materials and reduce associated costs. Road construction was undertaken by a licensed mining services contractor (IUJP) responsible for coal

hauling and road maintenance. The activities were supervised by the researcher as a representative of the mining permit holder.



Figure 1. Location Map of PT MAL

The research was conducted over 3 months, adjusted to the company's ongoing project. The activity schedule, which starts with Phase 1 in November 2025 and targets the thesis examination in December 2026, is shown in Table 1.

Table 1. Research Activity Schedule

No.	Activity	Nov-25	Dec-25	Jan-26	Feb-26	Aug-26	Sep-26	Oct-26	Nov-26	Dec-26
1	Literature study	●	●							
2	Problem identification and research objectives		●	●	●					
3	Initial data collection			●	●					
4	Proposal preparation				●	●	●			
5	Proposal seminar							●		
6	Field observation							●	●	
7	Sampling							●	●	
8	Data processing and analysis							●	●	
9	Report preparation							●	●	
10	Research results seminar							●	●	
11	Thesis report refinement								●	●
12	Thesis examination								●	●

Note: Phase 1 (Nov-25 to Jan-26) = preparation before the proposal; Phase 2 (Feb-26 to Sep-26) = research implementation; Phase 3 (Oct-26 to Dec-26) = results and conclusions.

Type of Research

This study is applied research aimed at examining the use of FABA as a construction material for coal haul roads at PT MAL. The approach is descriptive quantitative with a case study method, namely observing, measuring, and analyzing the application of FABA under actual field conditions. The study focuses on three main aspects: the technical aspect, the construction performance aspect, and the economic aspect. The population and sample are the direct calculation of the thickness of the materials on the coal haul road.

Data Collection Technique

Primary data were obtained by measuring road dimensions with a measuring tape, the actual thickness of the FABA and split stone layers, CBR or bearing capacity according to the available testing method, and stability or surface deformation such as settlement or rutting that can be observed or measured. Operational comparison data include segment length, width, grade, vehicle type or capacity, and traffic intensity during the same observation period. Secondary data were obtained through literature and institutional studies, namely national and international journals, previous research results, literature, company reports, technical specifications, and other sources related to the research problem.

Data Processing and Analysis Technique

Data were processed and analyzed quantitatively using *Microsoft Excel* based on field measurements, aerial photographs, documentation of surface conditions, and cost data. The analysis was designed to produce an objective comparison between two construction methods, namely a road using split stone only and a road using FABA and split stone. The road was formed with dimensions in accordance with regulations and internal company policy, after which the

material was compacted with a *compactor* according to the work procedure. For the FABA and split stone method, the thickness and composition of each layer and the compaction process were recorded, followed by the measurement of CBR or bearing capacity, density, actual thickness, and stability or deformation indicators, while the surface condition was recorded before and after the road was used by vehicles under the same observation conditions.

The volumes of FABA and split stone used, material costs, transport costs, equipment costs, and relevant work costs were then recorded, and the total cost and unit cost of each method as well as the percentage of cost savings were calculated. The economic results were analyzed together with the technical performance so that recommendations are based not only on lower costs but also on the fulfilment of road performance. The comparison was made under equivalent conditions so that differences in results can be attributed to the material method used. The parameters used in the analysis are shown in Table 2.

Table 2. Technical and Economic Performance Comparison Parameters

Parameter	Split stone	FABA and split stone	Basis of evaluation
Road dimensions	Measured	Measured	Length, width, and grade
Layer thickness	Measured	Measured	Actual thickness of each layer
Density	Measured	Measured	Field density test results
CBR/bearing capacity	Measured/test results	Measured/test results	Segment bearing capacity value
Stability or deformation	Measured	Measured	Settlement/rutting/surface change
Surface condition	Observed before and after traffic	Observed before and after traffic	Same observation period
Traffic load	Recorded	Recorded	Vehicle type, capacity, and intensity
Construction cost	Calculated	Calculated	Total cost and unit cost
Cost efficiency	Comparison basis	Comparison basis	Percentage of savings relative to the split stone method

Research Flow

The research was carried out because the cost of haul road construction is quite high, so the company sought another solution to the use of split stone. It started with a literature study related to haul road construction using FABA, including haul road construction without FABA in previous years at the company, followed by the production of primary data directly during the construction of the coal haul road, which was then processed in *Excel* to obtain the economic calculation. The research flow is shown in Figure 2.

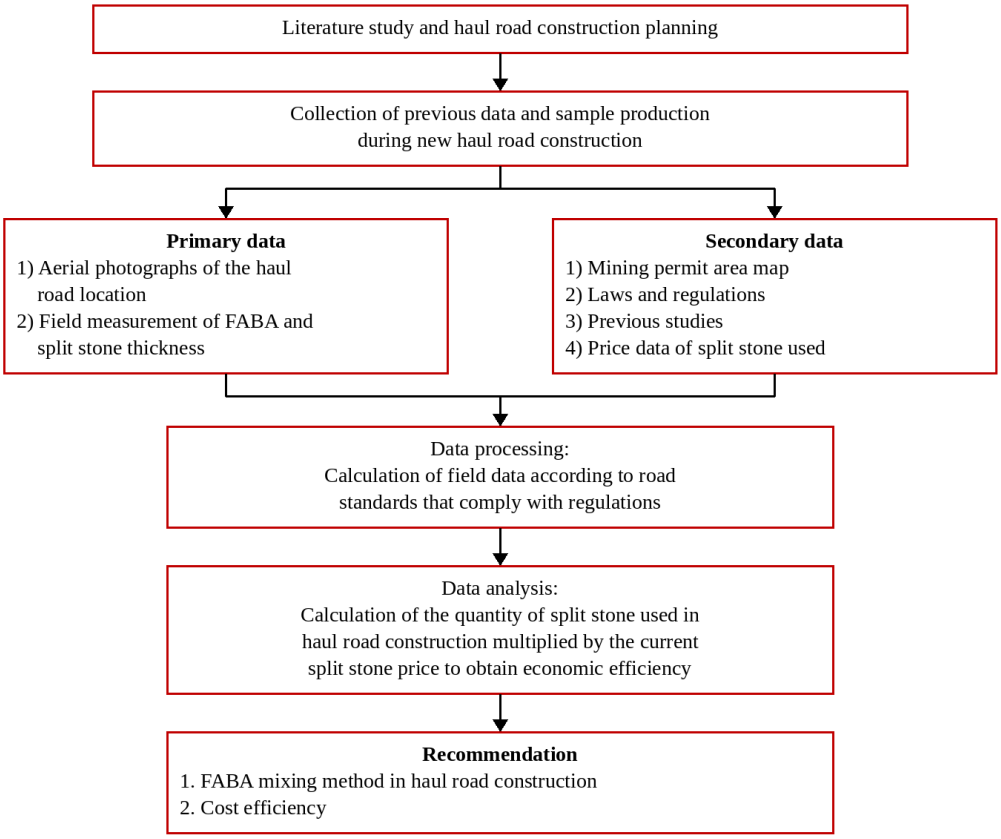


Figure 2. Research Flowchart

RESULT AND DISCUSSION

General Overview and Regulatory Basis of FABA Use

PT MAL sends 100% of its coal production to a mine-mouth power plant in South Sumatra, PT DSSP Power Sumsel. Coal combustion in the *boiler* produces *fly ash* and *bottom ash* (FABA), which is then disposed of at the final disposal site. FABA became of interest because, based on Government Regulation No. 22 of 2021, it was removed from the list of B3 waste and its status changed to non-B3 waste, which became the basis for using FABA rather than leaving it wasted at a disposal site licensed by the Environmental Agency of South Sumatra Province. Since the coal haul road had so far been formed with a split stone layer, the company sought to reduce its construction cost through trials of FABA as an initial layer before the split stone layer and of FABA as a full layer for the hauling road; from several trials, a mixing and working method was obtained that reduced split stone costs and has since been used for every new haul road construction and road maintenance.

Haul Road Construction Requirements and Historical Costs

Coal mining requires a special haul road that serves as the coal transport route from the mining area to the power plant. The load of a Hino ten-wheel *dump truck* is 28–30 tons per load, while the empty dump truck weighs 13 tons, so the haul road must have a strong and stable structure that is resistant to deformation. Split stone is one of the main materials used for pavement,

the lower foundation layer, and surface drainage because of its good mechanical properties, so its proper selection and use strongly determines the service life and operating costs of the haul road. The criteria for mining road construction based on Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM/2018 are summarized in Table 3.

Table 3. Mining Road Construction Criteria Based on Kepmen ESDM 1827 K/30/MEM/2018

Criterion	Requirement
Definition of mining road	A special road in the mine or project area consisting of production roads (used by heavy hauling equipment for overburden, mined material, and supporting activities) and supporting roads (for transport of goods/people)
Road width	Considers the largest hauling unit: at least 3.5 times its width for two-way roads and 2 times for one-way roads; bridges follow the same rule
Safety berm/bundwall	Required on the outer side of the road body; minimum height ¾ of the largest wheel diameter, considering runoff and loose material
Cross-fall/cross slope	At least 2% along the production road body to drain runoff
Grade	Maximum 12%; above 12% requires a technical study (risk, hauling unit specification, road material, stability, and drainage)
Intersection angle	Minimum turning angle at a T-junction of 70°
Lane separator	Required at bends and intersections; minimum height ½ of the largest wheel diameter and top width at least equal to the largest wheel width
Drainage system	Designed along the road to drain the highest runoff and maintained to prevent erosion, ponding, and structural damage
Bend radius and superelevation	Calculated to withstand lateral forces of mine trucks at the specified speed
Road maintenance	Periodic maintenance including grading, berm repair, drainage, and surface stability
Bearing capacity	Must be higher than the largest static load of vehicle plus payload (technical analysis required)

As mining progresses, split stone has become one of the largest cost contributors every year, so an *improvement* was made to reduce its use as the main haul road material. From 2020 to 2023, coal haul roads at PT MAL were relocated several times: in 2020 because the mining direction required the opening of two pits due to land that had not yet been acquired (the DS road was 4.252 km long), in 2021 because the old haul road was to be backfilled (IPD), and in 2022 to maximize coal mining *recovery*. The construction costs of these haul roads are presented in Table 4. In the construction of the old haul road at Pit DU, split stone was used dominantly without FABA, so the costs were quite high; with an actual split stone thickness of 20 cm (0.20 m), a 100 m long and 9 m wide segment required 180 m^3 of split stone.

Table 4. Haul Road Construction Costs, 2020–2022

Year	Total haul road construction cost (Rp)	Cost per meter (Rp/m)
2020	5,164,879,180	1,214,694
2021	1,849,396,510	900,388
2022	778,831,435	862,493

Conventional Method Using Split Stone

The planned relocation and construction of the coal haul road at Pit BL2 without FABA has a road length of 615 m, a width of 10 m, and a split stone thickness of 0.20 m. The material volume is calculated as length × width × thickness, namely 615 × 10 × 0.20 = 1,230 m³; at a unit price of Rp 499,000/m³, the estimated split stone cost is Rp 613,770,000 (Table 5). This figure represents the cost of split stone material based on the planned dimensions, not the total cost of all construction work. The cross-section of haul road construction at Pit BL2 is illustrated in Figure 3.

Table 5. Parameters and Cost Values of the Conventional Method

Parameter	Conventional method value
Road length	615 m
Road width	10 m
Split stone thickness	0.20 m
Split stone volume	1,230 m³
Unit price	Rp 499,000/m³
Split stone cost	Rp 613,770,000

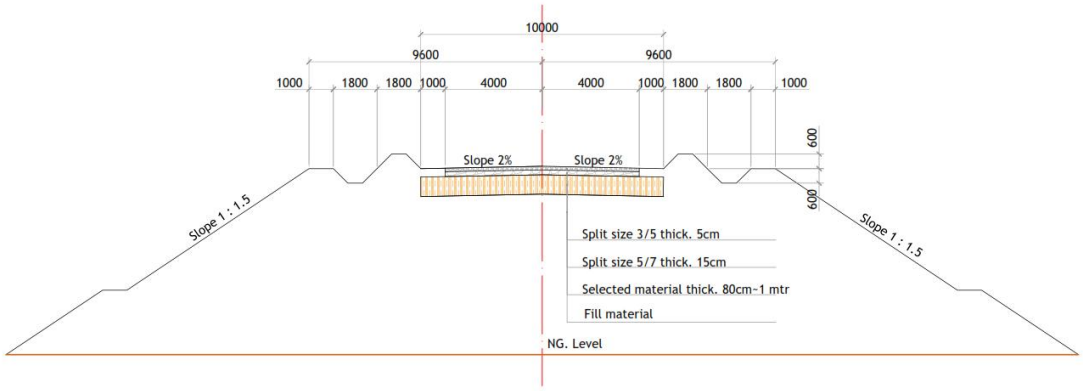


Figure 3. Illustration of Coal Haul Road Construction at Pit BL2

FABA and FABA + Split Stone Method

In the alternative method, the road body uses a FABA layer with a thickness of about 50 cm. Field CBR data were obtained for the 50 cm FABA material with three compaction methods: M1 (one layer of 50 cm), M2 (two layers of 25 + 25 cm), and M3 (three layers of 20 + 15 + 15 cm), as shown in Figure 4. Method 3 gave the best result from several samples, with the first layer of

20 cm compacted for about 22.9 hours, followed by the second and third layers of 15 cm each, also compacted for about 22.9 hours per layer.

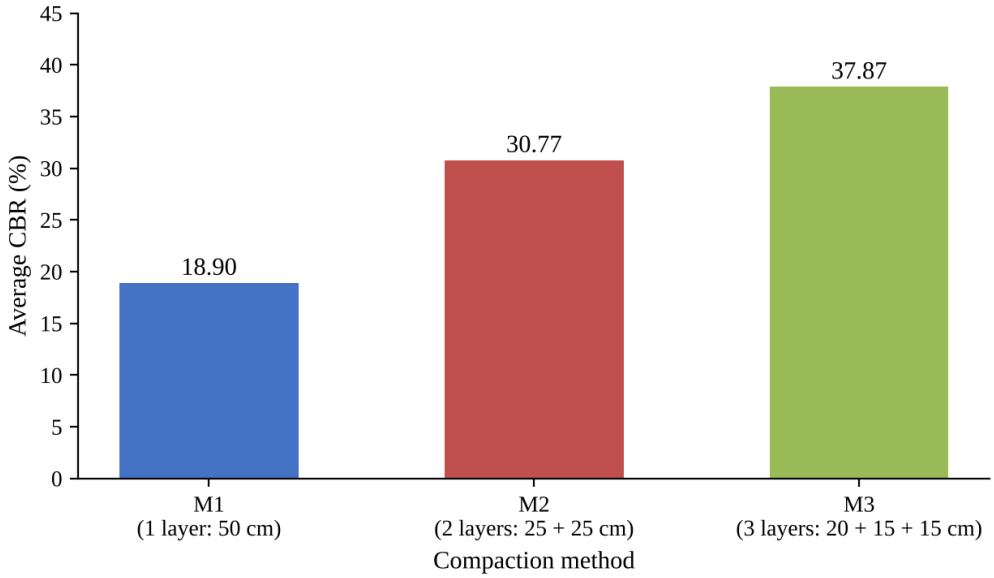


Figure 4. Average CBR Values with Three Compaction Methods

After compaction, a *bumpy* (undulating) surface was found on the entry and exit access to the mine, so split stone was added only in those areas, while the road body used FABA only (Figure 5). Field data recorded split stone areas of 177 m and 65 m in length, with a width of 12 m and a calculated thickness of 0.10 m. The parameters and costs of the method using 50 cm FABA and 10 cm split stone + 50 cm FABA at the entry and exit are presented in Table 6. For a total haul road length of 615 m, with 242 m of FABA + split stone and 373 m of FABA only, the total split stone cost is Rp 144,909,600.



Figure 5. Material Partition of the Coal Haul Road Construction

Table 6. Parameters and Cost Values Using FABA

Parameter	Thesis data/calculation result
FABA layer thickness	± 50 cm
Length of split stone area	177 m + 65 m = 242 m
Width of split stone area	12 m
Split stone thickness	0.10 m
Calculated split stone volume	242 × 12 × 0.10 = 290.4 m³
Split stone unit price	Rp 499,000/m³
Split stone cost	Rp 144,909,600
FABA compaction time	22.9 hours

Based on the mining and disposal direction in 2026, the transitional haul road will be used as a disposal area to meet future disposal needs, so the haul road must be relocated to support coal hauling and loading activities at Pit BL2 (Figure 6). The transitional road is also at risk of flooding because its elevation is +17.97, while the current sump elevation is +14.95. With a length of 242 m, width of 12 m, thickness of 0.10 m, and grade of 5.18%, the split stone volume is 290 m³, and

at Rp 499,000/m³ its total cost is Rp 144,909,600; with a total 2022 coal production of Pit BL2 of 82,565 tons, this corresponds to Rp 1,755/ton.

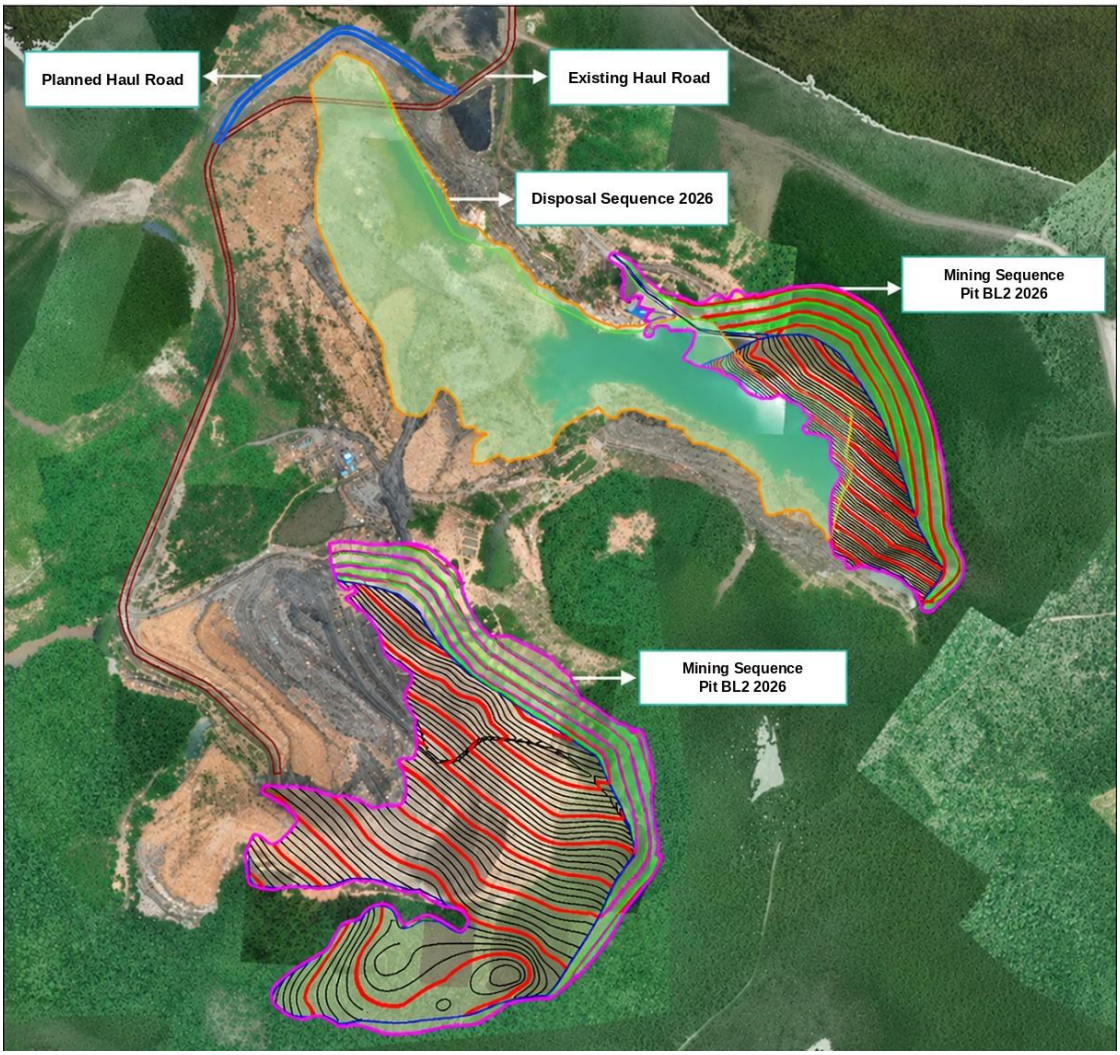


Figure 6. Construction of the Transitional Coal Haul Road

Comparative Analysis of Split Stone and FABA Costs

Table 7 compares the two road construction methods with the same road dimensions; the difference lies only in the construction material and road segments. The difference in split stone material cost is Rp 613,770,000 – Rp 144,909,600 = Rp 468,860,400. Relative to the material cost of the conventional method, the indicative reduction in split stone cost is about 76.39%. This interpretation must be limited to the calculated split stone component, because the costs of FABA, transport, heavy equipment, labor, compaction, drainage, and maintenance have not yet been fully summed; thus, the 76.39% figure is not a validated total construction saving.

Table 7. Comparison of the Conventional Method and FABA

Indicator	Without FABA	FABA + split stone
Calculation basis	615 × 10 × 0.20 m	242 × 12 × 0.10 m (split stone area)
Split stone volume	1,230 m³	290.4 m³
Split stone cost	Rp 613,770,000	Rp 144,909,600
Cost difference	Rp 468,860,400	

Discussion Based on Previous Studies

Samosir et al. (2021) tested FABA mixtures for the road *subbase* layer through soaked CBR tests and reported a CBR of 64% for the mixture without FABA, 93% for the 22% FABA variation, 84% for the 25% FABA variation as a substitute for fine aggregate, and 73% for the 25% FABA variation as an additive. All variations met the minimum *subbase* CBR requirement of 60% used in that study, showing that the effect of FABA on bearing capacity does not always increase linearly and that the proportion and manner of FABA use in the mixture affect the results. These laboratory findings indicate that FABA has the potential to be used in road pavement layers, but the CBR values of laboratory specimens cannot be directly regarded as the CBR value of the road at PT MAL, because the form of application, subgrade condition, material composition, compaction method, moisture content, and traffic load may differ.

Hilman et al. (2024) examined the composition of *fly ash* and *bottom ash* as road foundation material with cement or lime binders, testing *fly ash*:*bottom ash* ratios of 100:0, 75:25, 50:50, 25:75, and 0:100. The 50:50 ratio was reported as the initial optimum composition with a soaked CBR of 17.03%; with 7% cement, the soaked CBR reached 75.68% and the unconfined compressive strength (UCS) 21.448 kg/cm², while with 6% lime the soaked CBR was 60.16% and the UCS 27.70 kg/cm². These results confirm that FABA cannot be treated as a material with fixed performance without considering its composition and mixture treatment, and that FABA alone does not necessarily meet the foundation layer criteria; binders can significantly change bearing capacity and compressive strength, but with consequences in material cost, mixing, quality control, and environmental considerations.

The figures from the two studies cannot be compared directly as a performance ranking because the composition, layer function, test procedure, and specification criteria are not fully the same, but both consistently indicate that FABA evaluation must be based on testing of the material and mixture actually to be used. Other references, namely Amin et al. (2024), Ayuningtyas et al. (2022), Indriyati et al. (2019), and Isnandar et al. (2024), as well as publications of the Ministry of Energy and Mineral Resources (Kementerian Energi dan Sumber Daya Mineral, 2021) and the Ministry of Public Works and Housing (Kementerian Pekerjaan Umum dan Perumahan Rakyat, 2022), show the scope of FABA studies in pavement mixtures, construction materials, paving blocks, and waste management. In the context of this study, FABA was used as the main road-body layer about 50 cm thick, while split stone was used on the entry and exit access whose surface required improvement. This differs from laboratory studies that prepare measured mixtures for *subbase* or base layers, so the contribution of this field study is the documentation of the application and the calculation of split stone needs under actual operational conditions, while proof

of bearing capacity and long-term stability still requires field testing or representative material samples.

The testing framework of Samosir et al. (2021), covering material characteristics, aggregate gradation, and soaked CBR, is relevant as a reference for selecting evaluation parameters for the haul road, especially bearing capacity and density, although tests for mine roads must be selected based on project specifications and field conditions. The available thesis data do not yet include field CBR, density, deformation or *rutting* values, or monitoring of road conditions after vehicle traffic, so the technical results are explained through the construction method and observation of surface conditions rather than a quantitative claim that the bearing capacity has met the standard. The field evaluation parameters and verification needs are summarized in Table 8.

Table 8. Field Data Evaluation Parameters

Evaluation parameter	Available data	Analysis and verification needs
Material thickness	FABA ±50 cm (split stone 10 cm on the mine entry and exit access)	Verification of actual measurements at several points
Density	Compaction with a compactor for 22.9 hours	Density test and record of moisture content or compaction method
CBR/bearing capacity	Average of samples in method 3: 37.87%	Taking several samples after compaction
Stability/deformation	Note of *bumpy* access areas after compaction	Measure rutting and settlement and document conditions periodically
Surface condition	Split stone added on the entry/exit access	Compare conditions before and after traffic over the same period
Traffic load	Coal payload of 28–30 tons with a Hino unit weight of 13 tons	Record vehicle type, payload, and traffic intensity

Economic and Operational Implications and Limitations

Operationally, using FABA as the main road-body material and split stone only in areas requiring surface improvement has the potential to reduce the volume of conventional aggregate, which is relevant for companies that must relocate roads following mining progress. However, an implementation decision cannot be based only on the reduction in split stone purchases; the economic calculation needs to include the costs of obtaining and transporting FABA, equipment and working hours, labor, drainage work, repair needs, and road service life, with total cost per meter of road or cost per ton of coal hauled over the same evaluation period as more representative indicators. This study does not take these into account because FABA disposal from the power plant to the IUP area is carried out under a cooperation scheme with a permit for FABA disposal. The analysis was also conducted during a dry season that was longer and drier due to the El Niño phenomenon, which is one of the success factors of this study, learning from previous years when a *full* split stone layer was used. In addition, laboratory results from the reference journals are used as a scientific comparison, not as a substitute for testing on the studied haul road, and improved data are needed so that the technical–economic conclusions do not exceed the available evidence.

CONCLUSION

The FABA utilization method implemented on PT MAL's coal haul road involved placing FABA as the primary road embankment material at a total thickness of approximately 50 cm, compacted in three successive layers of 20, 15, and 15 cm. Each layer was compacted using a roller compactor for approximately 22.9 hours, achieving the highest average California Bearing Ratio (CBR) of 37.87% among the evaluated configurations. Crushed stone was applied only to the entrance and exit access roads of Pit BL2, where additional surface reinforcement was required. Construction activities were conducted during an extended dry season associated with El Niño conditions. Under the conventional construction plan, a road measuring 615 m in length, 10 m in width, and 0.20 m in crushed stone thickness required 1,230 m^3 of crushed stone, costing IDR 613,770,000. In contrast, the FABA-based construction method required crushed stone only along access road sections totaling 242 m in length, 12 m in width, and 0.10 m in thickness, resulting in a volume of approximately 290.4 m^3 and a material cost of IDR 144,909,600. This represented an indicative reduction of IDR 468,860,400 (76.39%) in crushed stone material costs. However, the comparison reflected differences in the dimensions and material requirements of the two construction configurations and did not establish equivalent total construction cost savings. Construction expenses were covered under the contractor's existing agreement, while FABA procurement, transportation, and other associated costs were not comprehensively evaluated. Future studies should compare road segments with equivalent dimensions, gradients, subgrade conditions, and traffic loads while incorporating all relevant cost components, including crushed stone, FABA procurement and transportation, equipment operation, compaction, labor, drainage, repairs, and maintenance. FABA mixture proportions and placement configurations should be determined through site-specific engineering assessments rather than solely maximizing waste utilization or directly adopting laboratory-derived optimum proportions. Further investigations should evaluate FABA's physical and chemical characteristics, moisture content, particle size distribution, compaction density, surface stability, and performance under varying weather and traffic conditions. Environmental risk assessments and verification of regulatory compliance should also be conducted before large-scale implementation.

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