Systemic Analytics

www.sa-journal.org

Research Expansion Alliance

Syst. Anal. Vol. 4, No. 1 (2026) 59–67.

Paper Type: Original Article

Performance and Cost Evaluation of Split–Local Material Mixtures for Coal Hauling Road Pavements: A Case Study in Coal Mining Operation

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Citation:

Received: 03 October 2025 *Revised: 11 December 2025* *Accepted: 07 January 2026*	Rahadi, W. A., & Hia, S. W. (2026). Performance and cost evaluation of split–local material mixtures for coal hauling road pavements: a case study in coal mining operation. *Systemic Analytics*, *4*(1), 59-67.

Abstract

Hauling road performance plays a critical role in maintaining productivity, safety, and cost efficiency in mining operations, particularly under heavy traffic and adverse weather conditions. In coal mining areas, haul roads are frequently subjected to high axle loads, moisture-induced deterioration, and rapid loss of bearing capacity. This study investigates the effectiveness of haul road strength improvement using a mixture of split stone and locally available material known as okes through a field-based case study in a coal mining operation in Central Kalimantan, Indonesia. The hauling roads were designed to accommodate haul trucks with gross vehicle weights up to 46 tons and an average daily traffic volume of 200 trucks. Two pavement improvement methods were evaluated: a conventional Split+Basecourse mixture and an alternative Split+Okes mixture. Road performance was assessed using key indicators, including California Bearing Ratio (CBR), slippery road duration after rainfall, surface deformation, and cost efficiency. The results show that both methods significantly improved road performance by reducing slippery conditions from four hours to one hour and increasing CBR values from below 10% to 72.94% and 64.50%, respectively. Although the conventional method achieved higher CBR values, the Split+Okes method delivered comparable operational performance with approximately 26% lower material cost. The findings demonstrate that the use of locally sourced materials provides a technically viable, cost-efficient, and sustainable solution for improving haul roads in mining operations.

Keywords: Hauling road, California bearing ratio, Local material, Mining infrastructure, Pavement performance.

1 | Introduction

Haul road infrastructure plays a pivotal role in sustaining productivity, safety, and cost efficiency in surface mining operations. In coal mining, transportation activities typically account for a substantial share of total operating costs, and hauling efficiency directly influences production continuity and unit cost performance.

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https://doi.org/10.31181/sa41202669

The structural condition of haul roads, therefore, becomes a critical determinant of overall mine performance, particularly under conditions of repetitive heavy axle loads, high traffic intensity, and adverse weather exposure.

In practice, mining haul roads are frequently subjected to extreme loading conditions due to the operation of heavy-duty haul trucks, with gross vehicle weights exceeding 40 tons. These loads, combined with high traffic frequency, accelerate pavement deterioration through mechanisms such as rutting, shear deformation, and progressive loss of bearing capacity. The situation is further exacerbated by rainfall, which promotes moisture ingress, weakens granular interlock, and significantly reduces surface friction. As a result, slippery road conditions often occur after rainfall events, leading to operational delays, increased fuel consumption, higher tire wear, and elevated safety risks [1–3].

Conventional haul road construction methods commonly rely on unbound granular pavement structures composed of compacted subgrade layers and crushed stone aggregates. While such systems are widely adopted due to their relative simplicity and flexibility, their performance is highly sensitive to material quality, drainage conditions, and maintenance practices. In remote mining areas, procuring high-quality base course materials often entails substantial transportation costs and logistical constraints, thereby increasing construction and maintenance expenditures. These challenges highlight the need for alternative pavement improvement strategies that maintain adequate structural performance while reducing material and operational costs.

The use of locally available materials has emerged as a promising approach to improving the sustainability and cost-efficiency of mining infrastructure. Locally sourced granular or gravelly materials can potentially reduce material transportation costs, shorten construction time, and lower environmental impact. However, concerns remain about the mechanical performance and durability of such materials when subjected to heavy-haulage traffic, particularly under wet conditions. Empirical field-based evidence is therefore required to assess whether locally available materials can provide sufficient bearing capacity, surface stability, and operational reliability when incorporated into haul road pavement systems.

This study investigates the performance of a haul road pavement improvement method using a mixture of crushed split stone and a locally available gravelly material known as okes, applied in a coal mining operation in Central Kalimantan, Indonesia. The hauling roads evaluated in this study are designed to accommodate haul trucks with gross vehicle weights up to 46 tons and an average daily traffic volume of approximately 200 trips, supporting an annual coal production target of around 800,000 tons. Two pavement improvement alternatives are comparatively assessed: a conventional Split+Basecourse mixture and an alternative Split+Okes mixture.

The performance of both pavement systems is evaluated using field-based indicators relevant to mining operations, including California Bearing Ratio (CBR), duration of slippery road conditions after rainfall, and material cost efficiency. By combining technical performance evaluation with economic analysis, this study aims to provide a comprehensive assessment of the feasibility of using locally sourced materials for haul road improvement.

The main contribution of this paper lies in presenting practical field evidence that locally available okes material, when combined with split stone, can deliver operational performance comparable to that of conventional base course mixtures at a significantly lower cost. The findings offer valuable insights for mining practitioners and infrastructure planners seeking technically viable, cost-effective, and sustainable solutions for haul road construction and maintenance in remote mining environments.

2 | Literature Review

Hauling road pavement is an engineering system designed to provide sufficient bearing capacity and surface stability to support repetitive heavy vehicle loading under harsh mining conditions. Conventional pavement systems are generally classified into flexible and rigid pavements. Flexible pavements rely on layered granular materials to distribute loads through stress attenuation, whereas rigid pavements transfer loads through slab action of concrete layers [4], [5]. In mining operations, however, the application of such conventional systems is often impractical due to high construction costs, long construction time, and limited accessibility in remote areas. As a result, mining haul roads commonly adopt unbound pavement structures consisting of compacted subgrade and crushed stone layers. These systems are economically feasible and operationally flexible but highly sensitive to traffic loading, moisture ingress, and material quality [6–8]. Pavement performance is therefore governed primarily by subgrade strength, aggregate interlock, drainage capability, and resistance to permanent deformation.

Traffic loading is a critical design parameter for haul road pavements and is typically represented by Average Daily Traffic (ADT) and axle load characteristics. In this study, the critical design vehicle is the FM Hino 500 haul truck with a 10-wheel configuration and a gross vehicle weight of approximately 46 tons. Such loading conditions generate high contact stresses and repeated load cycles, significantly increasing the risk of rutting and shear failure if pavement layers are inadequately designed [4].

According to AASHTO and Bina Marga design guidelines, the structural capacity of unbound pavement layers is commonly evaluated using the CBR, combined with cumulative traffic loading expressed as Equivalent Single Axle Load (ESAL) [9], [10]. CBR serves as an indicator of bearing capacity and shear strength of subgrade and base layers, while ESAL standardizes traffic-induced damage for pavement design purposes.

Mining haul roads are particularly susceptible to rutting, bearing capacity failure, and shear deformation, especially under wet conditions. Water infiltration reduces effective stress and weakens particle interlock, leading to a rapid decrease in shear strength and surface friction [11], [12]. These mechanisms often result in slippery road conditions after rainfall, causing operational delays and productivity losses.

To mitigate these issues, this study evaluates an alternative pavement improvement method that combines split stone with locally available material known as okes. Split stone provides a coarse load-bearing framework, while okes, a gravelly soil material, functions as a filler that enhances particle interlock and load distribution. Similar granular–soil mixtures have been shown to improve bearing capacity and reduce rutting susceptibility in unbound pavements [13].

Pavement strength was assessed using CBR testing in accordance with ASTM D1883 [13]. Two material combinations were investigated: Split+Basecourse and Split+Okes, each comprising 60% split stone (5/7 cm) and 40% filler material. The Split+Basecourse mixture increased CBR values from below 10% to 72.94%, while the Split+Okes mixture increased CBR values from approximately 6% to 64.50%. Although the conventional mixture achieved a higher CBR, the Split+Okes method demonstrated comparable bearing capacity with significantly lower material cost.

These findings indicate that locally sourced okes material can serve as an effective and economical alternative for improving haul road pavement. The approach enhances bearing capacity, reduces rutting potential, and improves operational reliability, thereby supporting sustainable, cost-efficient mining infrastructure development in remote regions [14], [15].

3 | Research Methodology

This study applies a comparative, field-based approach to evaluate the performance of two hauling-road pavement improvement methods in a coal mining operation in Central Kalimantan. The methodology begins with an assessment of existing road conditions, including visual inspection of surface distress, measurement of pavement layer thickness, and determination of initial subgrade strength using CBR testing. Traffic and loading characteristics were defined based on actual operational data, including haul truck configuration, gross vehicle weight of 46 tons, and an average traffic volume of approximately 200 trips per day. These parameters were used to estimate cumulative traffic loading in terms of ESAL for pavement performance evaluation. Two pavement rehabilitation methods were implemented: a conventional Split+Basecourse mixture and an alternative Split+Okes mixture, each consisting of 60% split stone (5/7 cm) and 40% filler material. Following construction, field monitoring was conducted to evaluate road performance under operational conditions. Performance indicators included post-repair CBR values, slippery road duration after rainfall, surface deformation, and overall road stability. Finally, the effectiveness of each method was assessed through a comparative analysis of structural performance and material costs, enabling evaluation of the technical feasibility and economic efficiency of hauling for road pavement improvement.

3.1 | Initial Condition Assessment and Primary Data Collection

Primary data collection was conducted to characterize the initial condition of the hauling road before rehabilitation. The assessment focused on identifying structural deficiencies, traffic loading characteristics, and environmental factors influencing road performance. The collected data included pavement surface condition (rutting, potholes, cracking, and slippery surfaces), existing pavement layer thickness, and the material composition of the road structure.

Traffic data were collected to determine the operational loading conditions, including the number of haul trucks per day, vehicle configuration, payload characteristics, and daily traffic distribution. Weather-related data, particularly rainfall frequency and intensity, were also recorded to evaluate their impact on pavement deterioration and surface slipperiness. These data provided the baseline for evaluating pavement performance before improvement.

3.2 | Field Monitoring and Damage Characterization

Following the initial assessment, field monitoring was conducted over a defined observation period to capture the progression and mechanisms of pavement damage. Visual inspections were performed to document road surface conditions before and after rainfall events, with particular attention given to rutting development, surface instability, and moisture-related degradation.

Quantitative measurements were also carried out, including rut depth measurement, identification of localized shear failure, and verification of pavement layer thickness. This monitoring phase enabled the identification of dominant failure modes and supported the selection of appropriate repair strategies.

3.3 | Pavement Improvement Implementation

Based on the results of the initial assessment and field monitoring, hauling road rehabilitation was implemented using two different material combination methods for comparative evaluation.

The first method employed a conventional Split+Basecourse mixture, consisting of 60% crushed split stone with a nominal size of 5/7 cm and 40% base course material. The existing deteriorated pavement layer was removed and replaced with the new mixture, followed by compaction to achieve the required density.

The second method used a Split+Okes mixture at the same proportion, with the base course material replaced by locally available okes material. Okes is a gravelly soil commonly found in the mining area and was selected due to its availability and cost advantage. The construction procedure for both methods was kept consistent to ensure comparability of results.

3.4 | Post-Repair Performance Evaluation

After the completion of pavement improvement works, the hauling road performance was systematically evaluated to assess the effectiveness of each material combination. The evaluation focused on four key aspects. First, physical road conditions were reassessed through visual inspection, emphasizing surface stability, rutting, and slippery conditions after rainfall. Second, pavement strength was quantified using CBR testing conducted before and after repairs. The increase in CBR values was used as the primary indicator of improvement in bearing capacity and shear resistance.

Third, operational performance was monitored by observing road behavior under repeated heavy vehicle loading, including pavement surface stability and the time required for the road to regain trafficability after rainfall. Finally, a cost analysis was performed by comparing material and construction costs for the Split+Basecourse and Split+Okes methods, enabling an assessment of cost efficiency relative to the achieved performance improvements.

4 | Results and Discussion

4.1 | Hauling Road Conditions Before Rehabilitation

Field observations indicate that the hauling road was severely deteriorated before rehabilitation. The pavement surface exhibited extensive potholes, cracking, and surface irregularities, which significantly disrupted hauling operations. Under wet conditions, the road surface became extremely slippery, resulting in frequent traffic interruptions and reduced hauling productivity, as illustrated in *Fig. 1*.

Fig. 1. Road conditions before repair.

The initial CBR of the subgrade was measured at less than 10%, indicating very low bearing capacity and insufficient resistance to shear deformation under heavy vehicle loading. Such low CBR values are typically associated with high susceptibility to rutting, surface instability, and rapid pavement degradation under repetitive axle loads.

4.2 | Reduction of Slippery Road Conditions After Repair

Following pavement rehabilitation, substantial improvements in surface performance were observed with both repair methods. As shown in *Fig. 2*, the duration of slippery road conditions after rainfall decreased from approximately 4 hours to 1 hour. This improvement was consistently observed for both the Split+Basecourse and Split+Okes pavement systems.

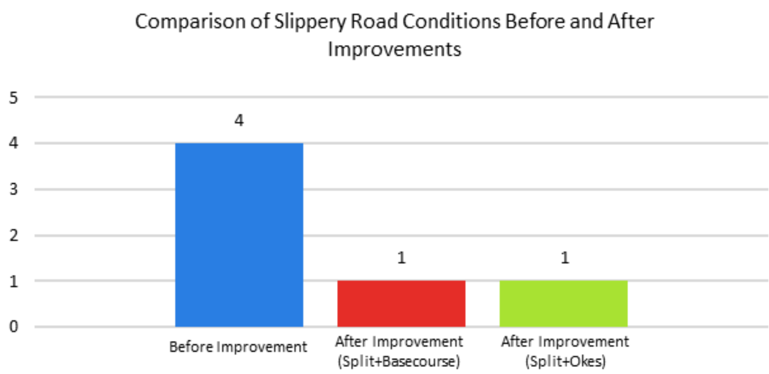

Fig. 2. Comparison graph of road slipperiness before and after repairs (in Hours).

The reduction in slippery time can be attributed to improved surface texture, enhanced particle interlocking, and better drainage characteristics provided by the split stone skeleton. The incorporation of either base course or okes material as a filler contributed to stabilizing the surface layer, limiting moisture retention, and maintaining adequate surface friction under wet conditions.

4.3 | Improvement in Soil Bearing Capacity (CBR)

The comparative CBR results before and after rehabilitation are presented in *Fig. 3*. Both pavement improvement methods resulted in a significant increase in soil bearing capacity. The Split+Basecourse method increased the CBR value from below 10% to 72.94%, indicating excellent structural improvement and high resistance to shear failure and permanent deformation.

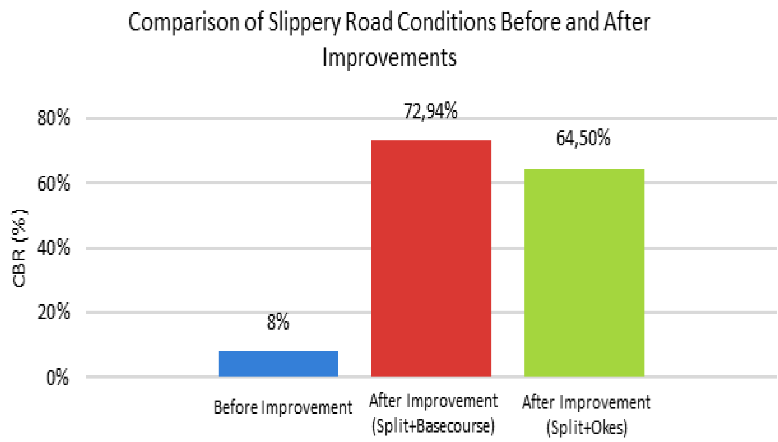

Fig. 3. CBR comparison chart.

The Split+Okes method also demonstrated a substantial increase in bearing capacity, with CBR values rising from approximately 8% to 64.50%. Although slightly lower than the Split+Basecourse method, the achieved CBR value still represents a significant improvement. It is considered adequate to support heavy-haul truck traffic in medium-scale coal mining operations. These results confirm that the use of locally available okes material, when combined with split stone, can effectively improve subgrade and pavement layer strength by enhancing load distribution and inter-particle contact.

4.4 | Visual Performance of Rehabilitated Pavement

Visual inspection of the hauling road after rehabilitation further supports the quantitative findings. *Figs. 4* and *5* illustrate the surface conditions after applying the Split+Basecourse and Split+Okes methods, respectively. Both pavement systems exhibited improved surface uniformity, reduced rutting potential, and better overall stability when subjected to repeated heavy vehicle loading.

Fig. 4. Road conditions using Split+Basecourse.

Fig. 5. Road conditions using Split+Okes.

No significant surface distress or localized shear failure was observed during the monitoring period, indicating that both material combinations were structurally effective under operational conditions.

4.5 | Comparative Cost Analysis

A comparative cost analysis of the two rehabilitation methods is presented in *Fig. 6*. The Split+Basecourse method required a material cost of IDR 660,000 per cubic meter, based on a 60% split stone (5/7 cm) and 40% base course material composition. While this method delivered the highest CBR improvement, its relatively high cost represents a significant consideration for large-scale implementation.

In contrast, the Split+Okes method achieved comparable performance at a lower cost of IDR 486,000 per cubic meter. This argument represents a cost saving of approximately IDR 174,000 per cubic meter, without compromising operational performance in terms of road slipperiness reduction and overall pavement stability.

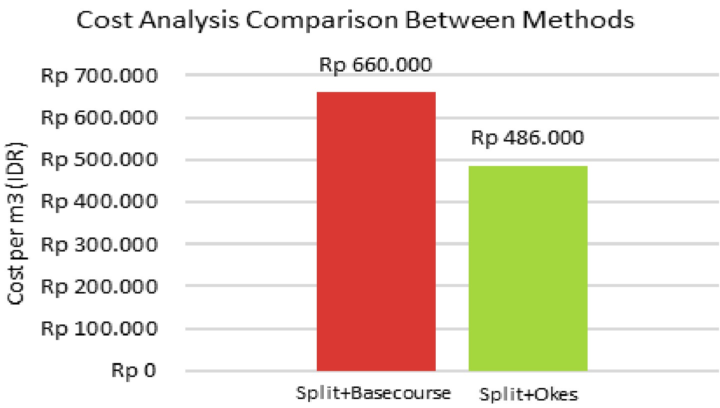

Fig. 6. Comparison chart of the cost analysis of the two methods.

From an economic perspective, the Split+Okes method offers a more cost-efficient solution, particularly for mining operations with extensive haul road networks and frequent maintenance requirements.

4.6 | Comparative Effectiveness of Pavement Improvement Methods

From a technical standpoint, the Split+Basecourse method provides superior improvement in bearing capacity, as reflected in the higher CBR of 72.94%. This argument indicates excellent load-bearing performance and long-term structural reliability. However, this advantage comes at a higher material cost.

The Split+Okes method, with a CBR of 64.50%, still demonstrates good structural performance and achieves the same reduction in slippery-road duration as the conventional method. Considering its significantly lower cost, this method represents a balanced solution between performance and economic efficiency.

4.7 | Pavement Thickness Design Based on ESAL

Pavement thickness design was conducted based on traffic loading and subgrade conditions. The primary design parameters included a gross vehicle weight of 46 tons, an average daily traffic volume of 200 trips, and a subgrade CBR of 8%.

The ESAL per trip was calculated using the following relationship:

$$\mathrm{ESAL} = \left(\frac{\mathrm{W}}{8.2}\right)^{1.2}.$$

Where W is the vehicle load in tons. Substituting the design vehicle load:

$$\mathrm{ESAL} = \left(\frac{46}{8.2}\right)^{1.2} = 7.37.$$

The annual cumulative ESAL was then calculated as:

$$\text{Total ESAL} = 7.37 \times 200 \times 365 = 536{,}185.$$

Based on the cumulative ESAL value and pavement thickness guidelines (*Table 1*), the optimum pavement thickness for the hauling road was determined to be in the range of 35–40 cm. This thickness is considered sufficient to accommodate the design traffic loading while maintaining acceptable structural performance for both Split+Basecourse and Split+Okes pavement systems.

Table 1. Thickness Hardness.

Pavement table AASTHO 1993	
Traffic (ESAL)	**Pavem Ent Thickness(cm)**
100.000	27
200.000	31.5
500.000	37
1000.000	43

5 | Conclusion

This study evaluated the performance of hauling road pavements constructed using two material combinations, namely Split+Basecourse and Split+Okes, under heavy traffic conditions in a coal mining operation in Central Kalimantan, Indonesia. The results demonstrate that both methods significantly improved road performance, particularly under wet conditions, by reducing slippery road duration after rainfall from approximately four hours to one hour. This improvement indicates enhanced surface stability and drainage characteristics, contributing to improved operational reliability. In terms of structural capacity, both methods substantially increased the CBR of the pavement layers. The Split+Basecourse method achieved a higher CBR value of 72.94%, while the Split+Okes method reached 64.50%. Although the conventional method provided a slightly greater increase in bearing capacity, the performance difference was not critical under the observed traffic loading conditions. The economic evaluation highlights the Split+Okes method as a more cost-efficient alternative, offering approximately 26% per cubic meter cost savings compared to the Split+Basecourse method. Considering its comparable mechanical performance and significant economic benefits, the use of locally available okes material presents a practical, sustainable, and technically viable solution for hauling road pavement improvement in mining operations.

Authors' Contributions

The authors conducted the research and prepared the manuscript, and have approved its final version.

Data Availability

The data are available from the corresponding author upon reasonable request.

Funding

This work was carried out without financial support from any public, commercial, or non-profit organizations.

Conflict of Interest

There are no competing interests to declare.

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