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COMPREHENSIVE REVIEW OF HAUL ROAD DESIGN METHODS: A COMPARATIVE APPROACH

The mining industry, primarily coal mines, has grown significantly, leading to heavy traffic on haul roads. However, inadequately designed haul roads often result in problems. The objective of the present study is to review and design the haul road using existing design methods and analyze their pavement design parameters. The study compares haul road design methods, including empirical California Bearing Ratio (CBR) methods, design charts, mechanistic design approach, and geocell reinforced design. This research enhances understanding of effective haul road design methods considering layer thicknesses, vertical strain, and deflections, thereby ascertaining the overall performance and suitability of each design approach**.** The mechanistic and reinforced design approaches emphasize pavement safety, significantly reducing vertical compressive strain. By using IITPAVE software, an optimal haul road design was found by finding vertical strains and deflections of various designs. Vertical strains ranged from 1238 to 3700 με, with 1.5 to 4.5 mm deflections. The outcomes indicate that both the mechanistic and reinforced approaches meet the criteria for critical strain limits (CSL). This study highlights the advantages of different design approaches to ensure cost-effectiveness.

Keywords: Mine Haul Roads; Empirical methods; Mechanistic design method; IITPAVE analysis; Reinforced design method

1. Introduction

India has an abundance of minerals, which are the foundation of any country's economic success. The mining industry in India is a crucial economic sector that substantially contributes to the national economy. The country's mining history reveals a significant focus on coal, lead,

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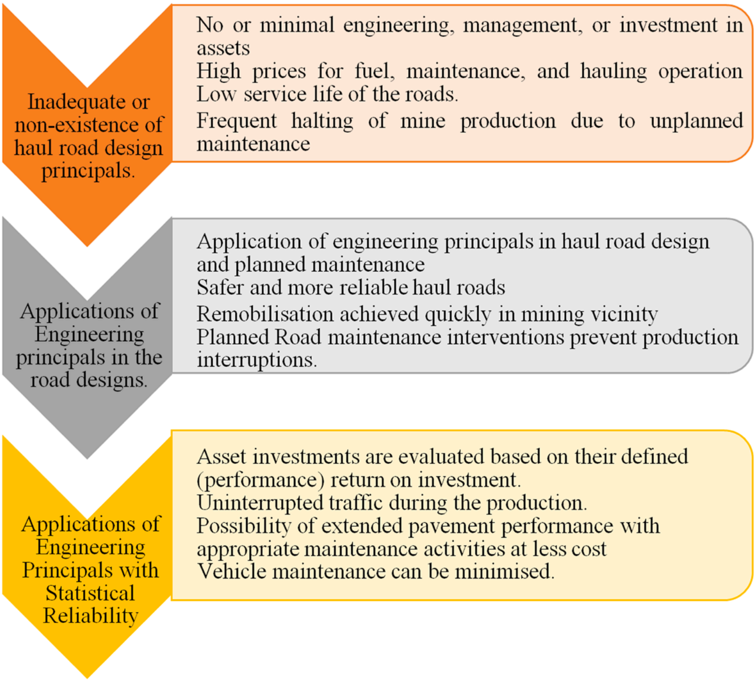
zinc, copper, lead ore, and other minerals. India has a rich mining heritage, dating back to 1774 when the first mining operations started in Raniganj, India [1]. Mining has always benefited the economy because of the raw materials, minerals, and metals it provides. Although the mining sector makes up only 2.5% of India's GDP, it still significantly contributes to its economy. In comparison, the mining sector's contribution to the entire industrial sector of GDP ranges between 10% and 11% in 2022 [2]. Coal mining accounts for 80% of all mining activities in India, and the haul roads of open-cast coal mines primarily utilize large dumpers for transportation. India's mining output increased by 9.80% in December 2022 compared to the previous year [3]. India ranks second in global coal production after China, with 761 million metric tons produced, and holds the fifth-largest coal reserves worldwide [2].

Mining activities are typically classed as either surface mining, conducted in open environments, or underground mining within tunnels or galleries. Haul roads hold a vital role in both conditions, enabling the transport of materials such as waste and ores from extraction sites to processing or disposal areas. Using locally available materials to construct these roads enhances sustainability and cost-effectiveness [4]. However, the constant traffic and heavy loads associated with mining operations often lead to rapid road degradation, necessitating costly repairs and modifications [5]. Addressing these challenges involves applying various highway engineering techniques customized to the unique conditions of each mining site. These factors include load-bearing requirements, traffic volume, material availability, road longevity, and financial considerations. Geovia Surpac and Fleet Management Systems are utilized in open-cast mining to monitor productivity, estimate deposit reserves, and plan efficient ore extraction methods, aiding in fleet estimation for haul road design. Software tools such as CIRCLY (Mincad, 2008), ELYSM5A (FHWA, 1985), KENPAVE, and IITPAVE [6] are employed for designing multilayered haul roads. Effective and profitable mining operations rely heavily on adequately designed, constructed, and maintained haul roads, given that transportation expenses constitute a significant portion of total mining costs.

The evolution of haul roads was initiated with inadequate or unavailability of design principles having a low service life of the haul roads with increased maintenance. To overcome the drawbacks, the haul road designs used engineering principles. By incorporating such principles, the roads have become more veritable and safer, which reduces repetitive road maintenance to avoid production interruption. In the later stages, including statistical inferences improves the uninterruptible traffic and maintenance management for performance optimisation. The evolution of haul roads is presented in detail in Fig. 1. This research commences a comparative study on the various haul road design methods with an illustrative example.

Ahlvin [7] introduced the mine haul road design method by using the California Bearing Ratio (CBR) in the empirical equation to calculate the layer thickness of the pavement. However, this method was found uneconomical as it provides a more significant layer thickness. Later, Kaufman & Ault [8] came up with an empirical design method using CBR and wheel load consideration to calculate the layer thicknesses of the pavement. Atkinson [9] introduced the design chart method, which was based on the CBR of the materials and truck wheel loads to determine the thickness of the pavement layers. Later, Thompson [10] modified this method by introducing the material characterization in the design chart, which is used to find the layer thickness of the haul roads. The mechanistic approach, a highway design methodology, was incorporated into the haul road design [11]. Later, it was modified based on the limiting strain criteria to obtain a safe design [12]. Moreover, an alternative approach was examined, which was initially designed for highway pavement construction but incorporated geosynthetics as reinforcement.

The application of this method is imperative for the improvement of haul road design. This method, employing a mechanistic approach, incorporates geosynthetic reinforcement materials to enhance strength characteristics, thereby reducing pavement thickness.



Inadequate or non-existence of haul road design principals.

No or minimal engineering, management, or investment in assets
High prices for fuel, maintenance, and hauling operation
Low service life of the roads.
Frequent halting of mine production due to unplanned maintenance

Applications of Engineering principals in the road designs.

Application of engineering principals in haul road design and planned maintenance
Safer and more reliable haul roads
Remobilisation achieved quickly in mining vicinity
Planned Road maintenance interventions prevent production interruptions.

Applications of Engineering Principals with Statistical Reliability

Asset investments are evaluated based on their defined (performance) return on investment.
Uninterrupted traffic during the production.
Possibility of extended pavement performance with appropriate maintenance activities at less cost
Vehicle maintenance can be minimised.

Fig. 1. Evolution of Mining Haul Roads Design Methods

2. Need for Better Haul Road Design

A proper haul road design is required to produce mine materials uninterruptedly. The lack of design standards and operational management input eventually leads to using an empirical design approach, which produces safe but inherently expensive and requires high maintenance. It can be challenging to pinpoint the root cause of an unsafe condition or design flaws contributing to poor performance or an accident. The empirical approach to haul road design is generally unsatisfactory due to the possibility of overspending on construction and operating costs. Over-designing and specifying roads, despite their higher initial construction costs, do not substantially reduce overall road-user costs for short-lived roads with low traffic volumes in a mining network. Poor road design and construction results in early failure, high truck operating costs, decreased productivity, and extensive maintenance. A brief discussion on the various haul road design methods and their evolution over time is discussed further.

Initially, Ahlvin [7] researched on behalf of the US Army Engineer Waterways Experiment Section to assess whether existing pavements could withstand the weight of a newly developed, significantly heavier aircraft. This comprehensive study involved various testing methods to evaluate pavement performance under diverse conditions, including static and dynamic loads, deflection, stress, and strain. Ahlvin's [7] work resulted in the development of a unique version of the CBR approach, specifically designed to address challenges caused by severe loads on pavements. Compared to existing non-engineered roads, the proposed approach lowered thickness requirements, making it particularly suitable and advantageous for developing haul roads subjected to heavy loads. In summary, haul roads are essential for the efficiency and cost-effectiveness of mining operations, often requiring customised design approaches. Ahlvin [7] pioneering research has significantly improved the design and construction of haul roads, enhancing their ability to withstand heavy loads and meet operational demands.

Later, Kaufman & Ault [8] identified a need to improve the haul road design approach to cater for the increase of truckload from 20 to 170 t. Despite the significant advancements in the machinery used in haul trucks, the technology required to construct the haul roads that these trucks travel on has not progressed at the same rate. Kaufman & Ault [8] aimed to address this issue by developing a design criterion with recommended practices to ensure continuity and safety on all haulage roads. Their study focused on creating a design manual covering various topics, including horizontal and vertical haul road alignment, haul road cross-section focusing on pavement design and drainage, and road maintenance.

Road designs in the 1980s primarily relied on the CBR method [13], which was satisfactory until larger 240 t trucks were introduced in 1995 [14-16]. Using these larger trucks on roads initially designed for 170 t trucks led to problems like extensive rutting and cross-section deterioration [16]. Consequently, a new design approach emerged in the 1990s, focusing on layer deflection to accommodate heavier loads. This revised design aimed for vertical deflections of less than 8.3 mm for 240 t trucks and 4.3 mm for 170 t trucks at the subgrade [16].

As the weight carried by the haul trucks increased and larger trucks were utilised, the maintenance costs of poorly designed roads would also increase, leading to a substantial increase in vehicle operating and maintenance expenses. Mining operations can fully realise the following benefits when the appropriate haul road design is selected based on the conditions: (a) A standard road that is safe for all users; (b) The lowest vehicle operating costs due to faster cycle times and higher productivity. (c) Reduced wear/tear of the tyres, frames, and suspension, resulting in improved asset utilisation and longevity of components.

It is essential to investigate the geological characteristics of the specific mine to accommodate the large haul truck loads.

The approach to mine road designs needs to consider and accommodate the capacity of haul trucks available to various types of mining operations to meet the requirements thoroughly and cost-effectively. With relatively rapid implementation, haul road management and design advancements can benefit long-term sustainability solutions. To minimise the problems associated with haul road design and management, Thompson & Visser [17] emphasised a holistic haul road design approach, incorporating structural, functional, and maintenance design elements, as shown in Fig. 2 [17]. Thompson later focused on pavement design while covering geometric design, maintenance, and performance evaluation.

Tennant & Regensburg [12] conducted a field survey to update the Canadian Mine Haul Road Manual, focusing on pavement design using calculated stresses, strains, and resilient modulus. A critical strain limit has been established to determine the required moduli for each layer and highlighted the importance of accounting for potential truck overloading during design. Thompson [10] performed comprehensive research, indicating that an optimal haul road, balancing construction cost and maintenance, lies between two extremes. One extreme is an expensive but

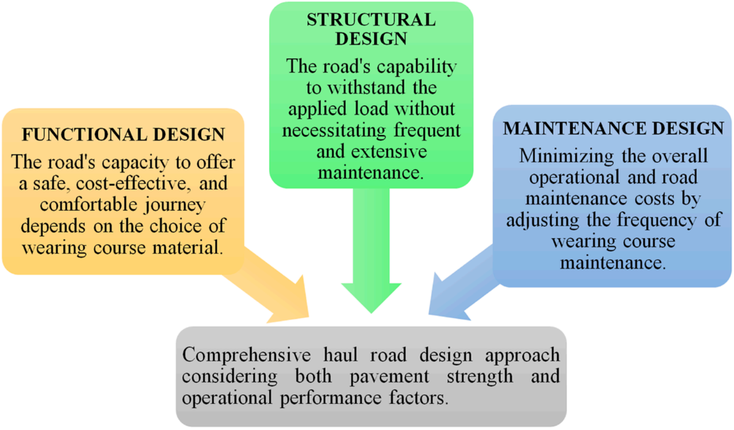


Fig. 2. Elements of an Integral Haul Road Design Strategy (Thompson & Visser, [17])

low-maintenance road, while the other is cheaper, with frequent repairs and high maintenance costs. Thompson [10] emphasises considering all design parameters during the initial stage to prevent substantial maintenance costs later in the road's service life.

Verma [18] has researched mechanistic design approaches for open-cast mine haul roads in India. A comprehensive design methodology was developed to address structural and functional road aspects. Factors like traffic characterisation, subgrade strength, pavement materials, and load distribution were thoroughly explored. The study consisted of field investigations, laboratory tests, and analytical modelling to assess road performance. This study provides critical insights into design parameters, material selection, and construction techniques tailored to Indian open-cast mines, underscoring the significance of accounting for geological and environmental conditions. The study culminates in recommendations for design and maintenance, offering valuable guidance for creating efficient and long-lasting haul roads in mining settings.

The use of geosynthetics in highway pavement construction has recently become increasingly significant. Reinforcing haul roads with geosynthetics enhances road stability. It indirectly protects the slopes or benches of open-cast mines from natural hazards like slope failure and erosion caused by heavy rainfall. This application offers the advantage of reducing pavement thickness, resulting in material and cost savings while enhancing structural strength compared to traditional methods. By considering the advantages of highway pavement with the reinforcement of geosynthetics, there is a chance of utilizing geosynthetics in haul road constructions. However, from the Indian perspective, there are no such provisions to incorporate geosynthetics in haul road constructions. In this study, an effort has been made to design the roads by following the design codes specified by the Indian Road Congress and AASHTO to incorporate the same design analysis used for highway pavements to be used in the design of haul road constructions. Many scientists [19-22], have already been working on improving the strength of the highways by reinforcing them with geosynthetic materials like Geogrid, Geotextile, Geocells, etc.

It has been noticed that the haul road design has evolved from the previous studies by various researchers' contributions. During the design phase, it is essential to consider all factors (wheel loads, tire pressure, CBR of the Subgrade, etc.) to identify the most appropriate approach for each mining operation. Compromising any of the components usually leads to a reduction in road performance. Merely increasing maintenance efforts is not a sufficient solution, as no amount of maintenance can rectify the issues caused by a poorly designed road. Hence, it is essential to thoroughly address each stage of the detailed design process to ensure optimal outcomes. A comprehensive analysis of various design parameters from existing haul road designs was conducted in the further section of the study to achieve an optimal haul road design.

3. Objective, Scope, and Methodology of the Study

The objective of the present study is to review and design the haul road using existing design methods and analyse their pavement design parameters.

To achieve the study objective, the following steps were taken:

Scope of Study:

- Study of different existing haul road design methods.
- Design of typical pavement sections using various haul road design techniques.
- Analysis of designed pavement sections, taking into account layer thicknesses, vertical strains, and deflections in the pavement.

The step-by-step procedure of the study is shown in the flow chart in Fig. 3. It begins with the identification of various pre-existing haul road designs. Each of these established methods

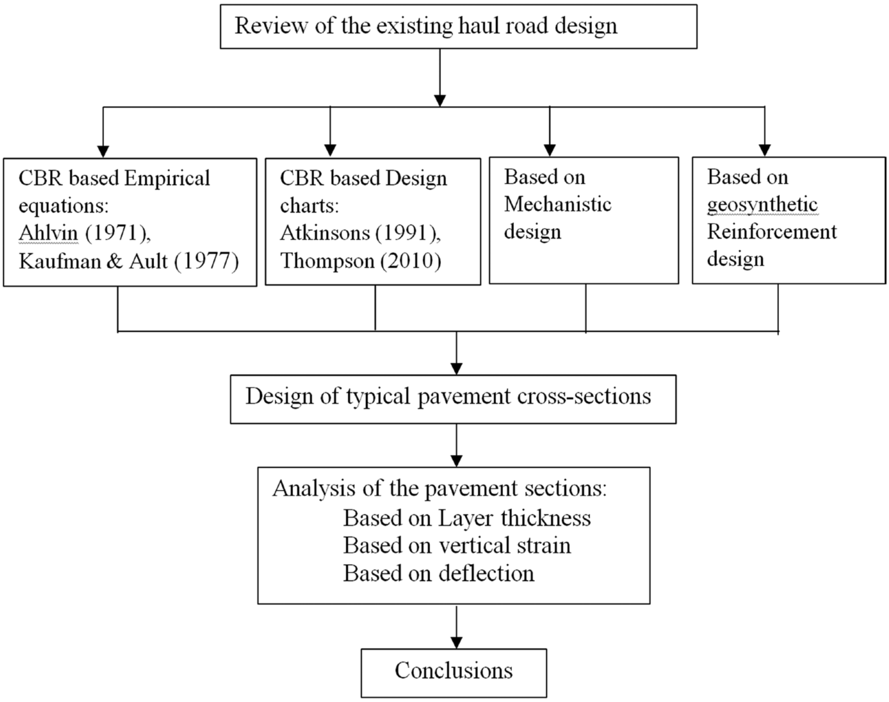


Fig. 3. Methodology of the Present Study

then undergoes thorough examination and analysis. Each existing method is designed during this phase, using predetermined data to ensure a standardised basis for comparison.

Subsequently, the study proceeds to a comparative analysis of each designed haul road section. This comprehensive analysis encompasses various critical factors, explicitly evaluating each design's layer thickness, vertical strains, and deflections. These elements are pivotal in determining the overall performance and suitability of each haul road design approach.

In the final stage of the study, conclusions and insights are drawn from the extensive comparative analysis. These findings are instrumental in offering a comprehensive understanding of the various haul road design methods, their strengths and weaknesses, and their applicability in different contexts. This structured process ensures a methodical evaluation of existing designs, contributing valuable insights to the field of haul road engineering.

Limit Bounds of the Study

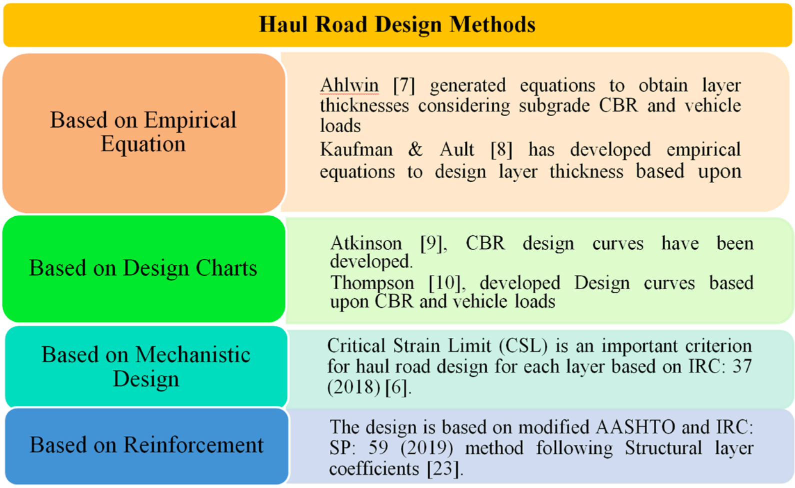
The present study aims to review and design haul roads using existing design methods and analyze their pavement design parameters. The research is limited to examining haul road design methods applicable to specific mining conditions, primarily focusing on Indian mining contexts. The study excludes consideration of design methods not relevant to haul road construction or those designed for different geological or operational contexts. The scope encompasses a comparative analysis of haul road design methods, focusing on layer thicknesses, vertical strains, and deflections. The research does not include field testing or validation of designed pavement sections but relies on theoretical analysis and comparison. The study emphasizes the importance of understanding the limitations and applicability of various haul road design methods within the specified mining context.

4. Mine Haul Road Design Methods

This study conducts a comprehensive comparative analysis of various haul road design methodologies, encompassing two equation-based methods, two design chart methods, a mechanistic design approach, and a reinforcement-based alternative approach, as illustrated in Fig. 4. Each method is discussed, exemplified by a haul road design scenario based on assumed parameters.

Historically, Ahlwin [7] and Kaufman & Ault [8] introduced empirical equations for mine haul road layer thickness design. Atkinson [9] devised a design chart based on the CBR approach, while Thompson [10] developed another chart that later underwent modification to align with Unified Soil Classification and ASTM/AASHTO standards. Advancements in computing technology have enabled mechanistic design approaches [11,18]. Software like KENPAVE, ELYSM5A (FHWA), CIRCLY (MinCad), and IITPAVE [6] facilitate multi-layer road design. Reinforcement-based designs have gained popularity, employing geosynthetics per IRC: SP:59-2019 [23]. These designs follow two approaches: the Mechanistic-Empirical Pavement Design Guide (MEPDG) method using Modulus Improvement Factor (MIF) and the Modified AASHTO method using Layer Coefficient Ratio (LCR).

Empirical design methods, including Ahlwin [7], Kaufman & Ault [8], Atkins [9], and Thompson [10], have their roots in years of pavement performance observations. The chosen Mechanistic design approach relies on 'linear elastic layered theory,' treating the pavement as a multi-layer system. It assumes the lowest layer is semi-infinite and the upper layers are horizontally infinite but of finite thickness. Key input parameters include elastic modulus, Poisson's ratio, and thickness for calculating stress, strain, and deflection resulting from surface loads.



Ahlwin [7] generated equations to obtain layer thicknesses considering subgrade CBR and vehicle loads

Kaufman & Ault [8] has developed empirical equations to design layer thickness based upon

Atkinson [9], CBR design curves have been developed.

Thompson [10], developed Design curves based upon CBR and vehicle loads

Critical Strain Limit (CSL) is an important criterion for haul road design for each layer based on IRC: 37 (2018) [6].

The design is based on modified AASHTO and IRC: SP: 59 (2019) method following Structural layer coefficients [23].

Fig. 4. Different Haul Road Design Methods

General information:

Various parameters are considered when designing mine haul roads using different methods based on specific design criteria. These criteria include a minimum assumed CBR of 5% for the subgrade [24,6]. Additionally, the CBR values for the GSB and Base layers are set at 30% and 80%, respectively, based on [6,24,25]. A design example using assumed data provides a practical illustration of each method. The design vehicle chosen for this example is the VOLVO FMx 500, a vehicle commonly used in mining operations [26]. Detailed information about the vehicle can be found in TABLE 1.

TABLE 1

Design Vehicle Information [26]

Haul Truck Type	VOLVO FMx 500
Axle Type	Tandem Axle (Dual tyre)
Tyre Pressure	700 kPa
Wheel Load	19 T
ESWL (20% of wheel load as per Kaufman and Ault, 1977)	22.8 T

Traffic calculation:

This study focuses on VOLVO FMx dump trucks, commonly used in Indian open-cast mines, with a specific examination conducted at the Umrer opencast coal mine near Nagpur, India, operated by Western Coal Limited (WCL). This mine transports approximately 4 million tons of coal annually, with an expected 25% growth in subsequent years from the current 3.2 million t [27]. Haulage trucks have a Gross Vehicle Mass (GVM) of 58 t and a 40 t average payload. The haul road is active for five years before scheduled maintenance and repair over its ten-year operational span. Over its lifetime, the road will carry a total load of 20 million tons, involving approximately 500,000 loaded trucks, equalling around 10 lakh load cycles for dual-axle dump trucks, excluding considerations for empty truck traffic.

4.1. Method I: Pavement Design as per Ahlvin Method (1971)

The research aimed to adapt the traditional CBR method to suit heavy-load pavements like haul roads and aircraft surfaces, resulting in Ahlvin's formula. It demonstrated that thinner layers were sufficient compared to the existing criteria for multiple-wheel loads. A cubic equation enhanced its ability to distinguish test failures from non-failures. As Ahlvin [7] suggested, Eqs. (1) & (2) calculates upper layer thickness to prevent shear deformation in underlying layers. It first determines the cover thickness and then subtracts it from the previous layer's cover thickness to establish the pavement's layer thickness.

As per Ahlvin's method, the thickness of the overlaying layer is given by

$$t = \sqrt{A}\left[\begin{array}{l} -0.048 - 1.1562\left(\log\log\dfrac{CBR}{Pe}\right) - 0.6414\left(\log\log\dfrac{CBR}{Pe}\right)^2 \\ -\ 0.4730\left(\log\log\dfrac{CBR}{Pe}\right)^3 \end{array}\right] \tag{1}$$

Were,

t – Thickness of Overlaying Layer (m)

$$A = \frac{Load}{Tyre\ pressure}\ (\mathrm{m}^2)$$

$$Pe = \frac{ESWL}{A}\ (\mathrm{t/m}^2) \tag{2}$$

Considering a load of 19 t, ESWL of 22.8 t, and tyre pressure of 700 kPa, the resulting A and Pe are 0.027 m^2 and 845 $\mathrm{t/m}^2$, respectively.

ESWL = 22.8 t;

Tyre Pressure = 700 kPa.

Now, an example is solved based on the general information data to find the overlying thickness of the pavement by substituting the parameters in Eq. (1). For each layer, the overlying thickness is calculated

The various steps to ascertain the thickness of each layer and the total cover are as follows and are depicted in the figure.

Step 1: Eq. (1) calculates the cover thickness for the Subgrade with a CBR of 5%, resulting in 0.751 m. However, to ensure adequate overlying thickness for the subgrade, a thickness of 0.80 m is chosen.

Step 2: Employ Eq. (1) to approximate a cover thickness of 0.35 m for the GSB Layer with a CBR of 30%. Consequently, the GSB Layer thickness is determined by subtracting this cover thickness (0.35 m) from the total thickness, yielding 0.45 m. Therefore, a GSB Layer thickness of 450 mm is recommended for a CBR of 30%.

In Step 3: Eq. (1) approximates a cover thickness of 0.20 m for the Base Layer with a CBR of 80%. Subsequently, the base layer thickness is determined by subtracting the cover thickness, resulting in 0.15 m. This establishes a base layer thickness of 150 mm.

Step 4: It reveals that the remaining layer thickness for the wearing course is 0.2 m, meeting the minimum depth requirement for the surface layer. This requirement should be at least 100 mm for a lifespan of less than one year or 200 mm for long-lasting roads. The calculated cover thickness and layer thickness are summarised in TABLE 2, while a schematic diagram illustrating the different pavement layers is presented in Fig. 5.

TABLE 2

Representing the Layer Thicknesses of the Pavement as per Ahlvin Method

Layer	CBR (%)	Cover (m)	Layer Thickness (m)
Subgrade	5	0.8	—
GSB	30	0.35	0.45
Base	80	0.2	0.15
Wearing	—	—	0.2

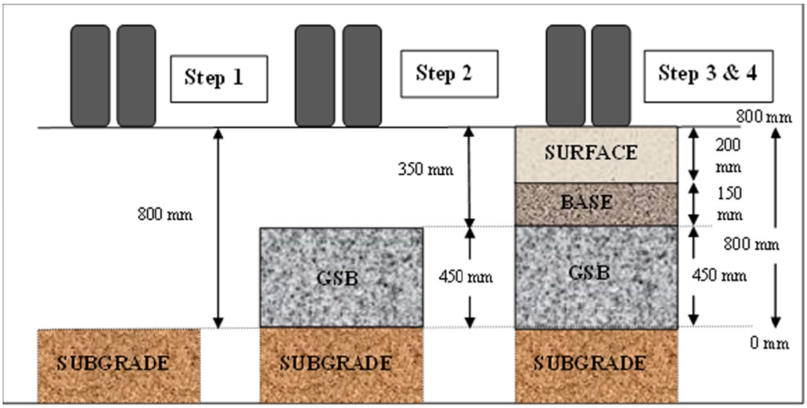


Fig. 5. Procedure for determining layer thickness by Ahlvin's Method

4.2. Method II: Pavement Design as per Kaufman & Ault [8]

In haul road design, the conventional practice involves considering the CBR values of in-situ materials for construction and design loads. The resulting design thickness is primarily concerned with providing a protective cover layer based on a specified support or CBR bearing capacity, without considering the strength and support of the layers above it. To account for the impact of dual tires, a 20 % increase in wheel load is applied [8].

Kaufman & Ault [8] formulated a semi-rational exponential Eq. (3), an empirical approach that can be utilized to estimate the necessary cover thickness (Z_{cbr}) for a material with a specific CBR. This design method calculates pavement cover thickness based on the wheel load and the CBR of the material. The same procedure applies to subsequent layers, with the crucial requirement that each successive layer must have a higher CBR value than the layer immediately beneath it.

$$Z_{cbr} = \frac{9.81 t_w}{P}\left[0.104 + 0.331 e^{\left(-0.0287 t_w\right)}\right] \times \\ \times \left[2 \times 10^{-5\left(\frac{CBR}{P}\right)}\right] \times \left[\left(\frac{CBR}{P}\right)^{-\left(0.415 + P \times 10^{-4}\right)}\right] \tag{3}$$

In the context of pavement design, Z_{cbr} represents the thickness of the overlying layer in meters. The variables t_w and P represent the truck wheel load, 22.8 t, and the tyre pressure, 700 kPa. These values are essential parameters used in calculating the overlying layer thickness to ensure adequate support and performance of the pavement structure under the specified loading conditions.

Later, the equation was modified to account for ESWL to obtain a more reliable estimation of the cover thickness Z_{ESWL} (m), A semi-rational estimation of the Equivalent Single Wheel Load (ESWL) can be employed, which is expressed by the following Eq. (4) as per Thompson (2010)

$$Z_{ESWL} = Z_{CBR} + \left[0.184 + \left(0.086 CBR + \frac{17.76 CBR}{t_w}\right)\right]^{-1} \tag{4}$$

Step 1: Based on Eq. (2), the overlying thickness (Z_{cbr}) for the subgrade with a CBR of5 % is calculated as 1.78 m. However, for practical and economic reasons, a rounded value of 1.8 m is chosen as the overlying layer thickness for the Subgrade.

Step 2: Using Eq. (2), the thickness of the overlying layer for the Granular Subbase (GSB) Layer with a CBR of 30% is computed as 0.496 m. For practical purposes, a rounded value of 0.5 m is selected as the overlying layer thickness for the GSB Layer. Consequently, the GSB layer thickness is calculated as 1.8 m – 0.5 m = 1.3 m.

Step 3: For the Base Layer with a CBR of 80%, the overlying layer's thickness is determined using Eq. (2), resulting in an overall thickness (Zcbr) of 0.135 m. For practical considerations, a rounded value of 0.2m is chosen as the overlying layer thickness for the Base Layer. Thus, the Base Layer thickness is calculated as 0.5 m – 0.2 m = 0.3 m.

Step 4: The remaining thickness for the wearing course layer is 0.2 m, which meets the minimum depth requirement for the Surface layer. This requirement should be at least 100 mm for a lifespan of less than one year or 200 mm for long-lasting roads. The schematic diagram for different pavement layers is shown in Fig. 6 below.

Following the above procedure, the subsequent layers' cover thickness and layer thicknesses are calculated using Eq. (4). The layer thicknesses of the pavements using Eqs. (3) and (4) are tabulated in TABLE 3 below.

TABLE 3

Representing the cover and layer thickness per the Kaufman & Ault method

Layer	CBR	Single Wheel (Eq. (3))			ESWL (Eq. (4))		
			Cover (m)	Layer Thickness (m)		Cover (m)	Layer Thickness (m)
Subgrade	5	Z_{cbr}	1.8	—	Z_{ESWL}	2.0	—
GSB	30	Z_{cbr}	0.5	1.3	Z_{ESWL}	0.6	1.4
Base	80	Z_{cbr}	0.2	0.3	Z_{ESWL}	0.3	0.3
Wearing			—	0.2			0.3

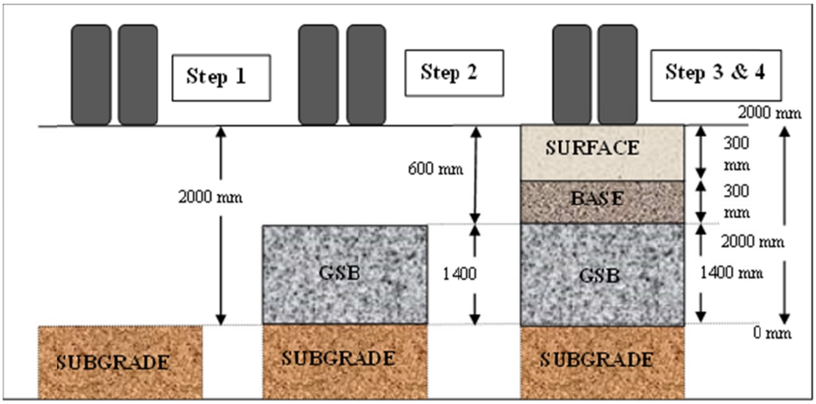


Fig. 6. Procedure for determining layer thickness by Kaufman & Ault Method

4.3. Method III: Design Based on Atkinson's Design Chart [9]

This road design method relies on the CBR of construction materials as a significant factor. Calculating wheel loads for haul trucks is straightforward, using the manufacturer's specifications. However, it is essential to consider that haul trucks are often loaded beyond their weight capacity. The loaded vehicle weight is divided over each axle by the number of tires on that axle to determine the maximum load on any wheel. Fig. 7 provides a design chart that facilitates the calculation of layer thicknesses for different CBR values based on the truck's wheel load (t). This method primarily depends on CBR to determine the total cover thickness over the in-situ subgrade materials. The step-by-step procedure for calculating pavement layer thickness using the design chart shown in Fig. 7 is outlined below.

Step 1: Considering the Subgrade's CBR value of 5%, the design chart (Fig. 7) suggests a cover thickness of 0.75 m for a wheel load of 22.8 t.

Step 2: Referring to the same design chart, a cover thickness of 0.25 m is determined for the Granular Subbase layer (GSB) with a CBR of 30%. Consequently, the GSB layer's thickness is calculated as 0.5 m by subtracting the cover thickness from the total thickness of 0.75 m. Therefore, the GSB layer is 500 mm thick in this design scenario.

Step 3: Using the design chart, a cover thickness of 0.15 m is determined for the Base Layer, which has a CBR of 80%. By subtracting this cover thickness from the total thickness of 0.25 m, the Base Layer is found to be 0.1 m thick. Consequently, the Base Layer is 100 mm thick in this design case.

Step 4: The remaining layer, which serves as the Wearing Course, has a thickness of 150 mm, meeting the minimum required criteria. The cover thickness and the layer thickness are documented in TABLE 4.

The schematic diagram of the pavement layer thickness is shown in Fig. 8.

TABLE 4

Cover and Layer thickness per Atkinson Design chart

Layer	CBR (%)	Cover thickness (m)	Layer thickness (m)
Wearing course	—	—	0.15
Base	80	0.15	0.10
Granular Subbase	30	0.25	0.50
Subgrade	5	0.75	—

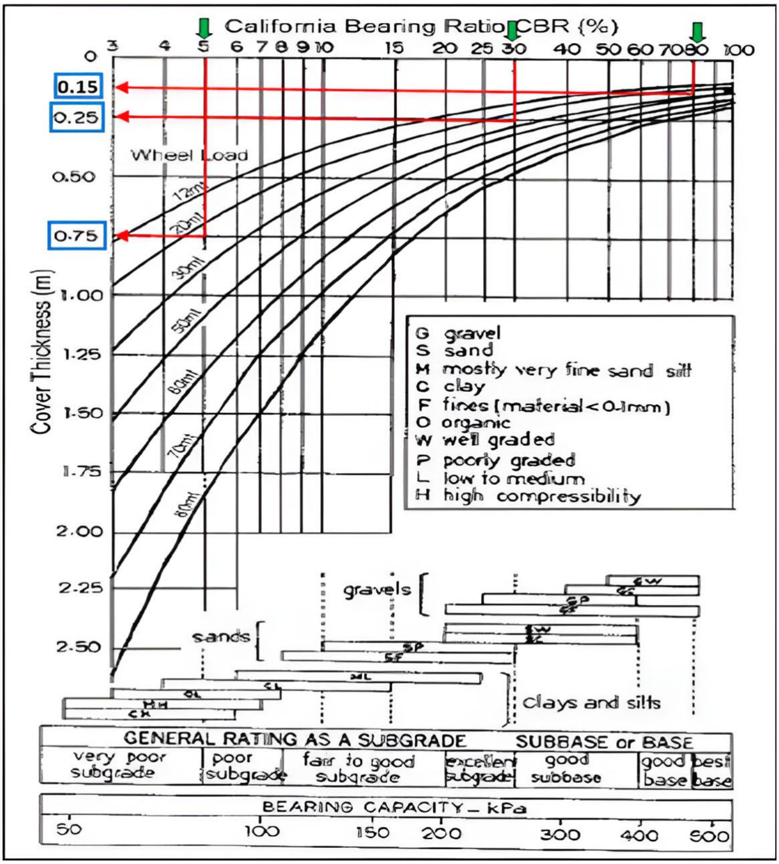


Fig. 7. Mine Haul Road Design Chart Based on Atkinson [9]

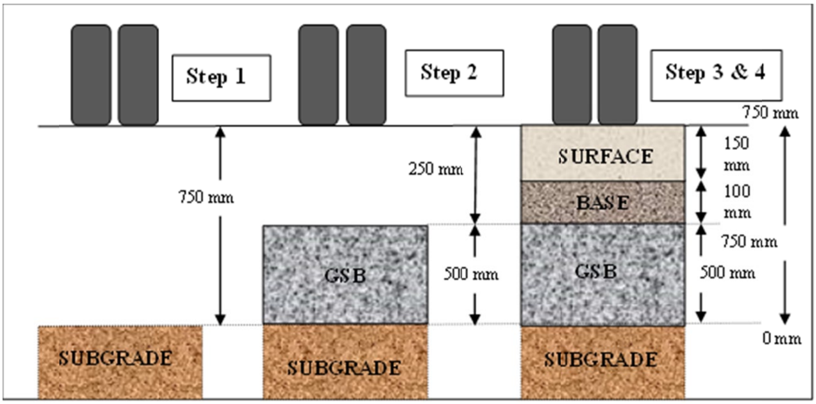


Fig. 8. Procedure for determining layer thickness by Atkinson method

4.4. Method IV: Design Based on Thompson's Design Chart [10]

In this design procedure, the pavement cover thickness above a material with a specific CBR is determined based on the applied wheel load and the CBR value of the material. This method can also be applied to successive layers, provided that each subsequent layer has a higher CBR than the preceding one. The modified metric version of the layer thickness design chart, depicted in Fig. 9, introduces notable changes. In the previous design chart, materials with a CBR of 100 were recommended to have at least 0.1 m of cover. However, in the modified version, all curves representing materials with a CBR of 100 now indicate zero thickness. This method employs design charts based on the CBR values of different layer materials relative to the wheel loads of dump trucks. Using the design chart shown in Fig. 9, specific layer thicknesses are determined for various CBR values at different layers, considering a wheel load of 25 t, corresponding to a truck GVM of 150 t.

Step 1: Considering a Subgrade with a CBR of 5%, the design chart created by Thompson recommends a cover thickness of 0.8 m or 800 mm.

Step 2: Examining the Granular Subbase (GSB) with a CBR of 30%, the design chart specifies a cover thickness of 300 mm. By subtracting this cover thickness from the total thickness of 800 mm, the GSB layer should have a thickness of 500 mm, thus recommending a GSB layer with a thickness of 500 mm.

Step 3: In the case of the Base Layer with a CBR of 80%, the design chart indicates a cover thickness of 100 mm. Subtracting this cover thickness from the total thickness of 300 mm, the Base Layer's thickness should be 200 mm.

Step 4: The remaining thickness for the Wearing course will be 100 mm, which does not satisfy the layer thickness requirement.

The thickness of the pavement layers is tabulated in TABLE 5, using the design chart and the schematic diagram of the pavement shown in Fig. 10.

TABLE 5

Represents Cover Thickness and Layer Thickness per Thompson's Design Chart

Layer	CBR (%)	Total cover (m)	Layer thickness (m)
Wearing course	—	—	0.1
Base	80	0.1	0.2
Granular Subbase	30	0.3	0.5
Subgrade	5	0.8	—

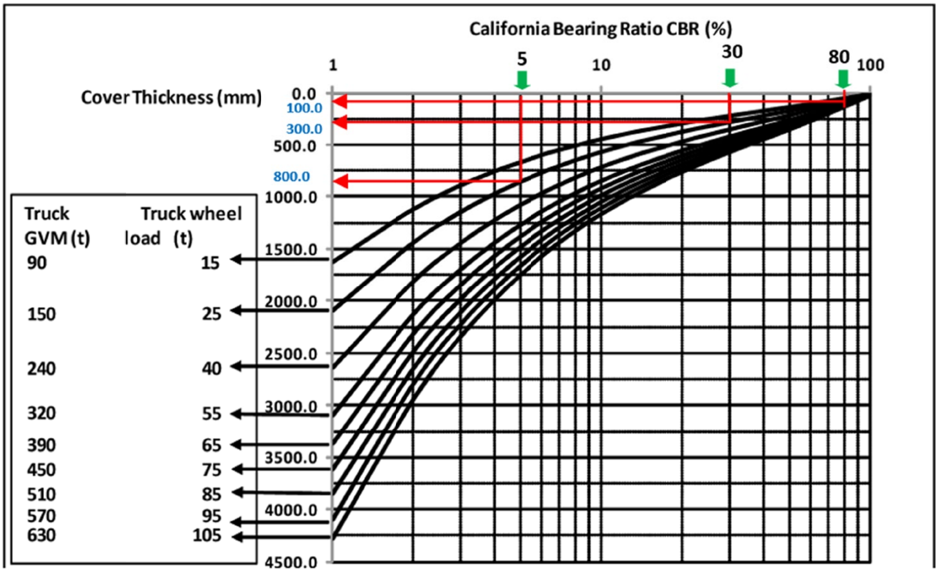


Fig. 9. Mine Haul Road Design Chart Based on Thompson [10]

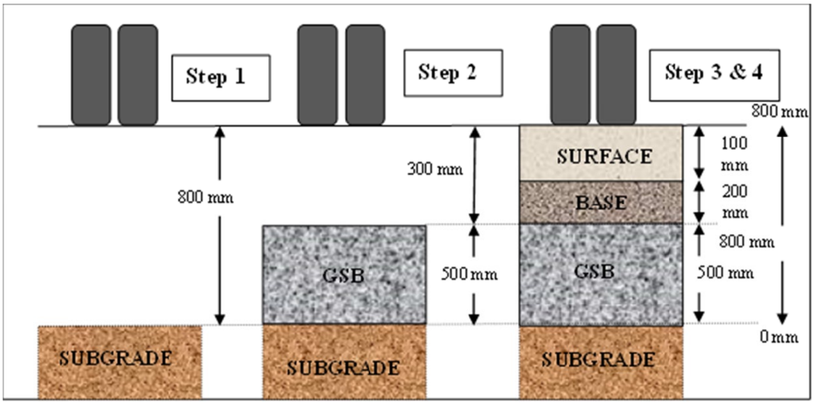


Fig. 10. Procedure for Determining Layer Thickness by Thompson Method

4.5. Method V: Design Based on Mechanistic Approach

The mechanistic design method for pavements, especially those used in haul roads, is an advanced approach that integrates ideas from mechanics and material science to forecast pavement performance under different loading circumstances. This approach utilises a fundamental comprehension of how materials react to loads, stress, and strain, enabling the creation of pavement designs that are more precise and dependable.

Fundamental concepts of Mechanistic design: The study of mechanics focuses on how materials behave under various forces and displacements. It includes ideas such as movement, external forces (such as axle load and load frequency), and the resulting internal forces within materials. Elasticity is the ability of materials to regain their original shape after a load is removed. The main variables to consider are stress, strain, deflection, Poisson's ratio, and elastic modulus [11,18].

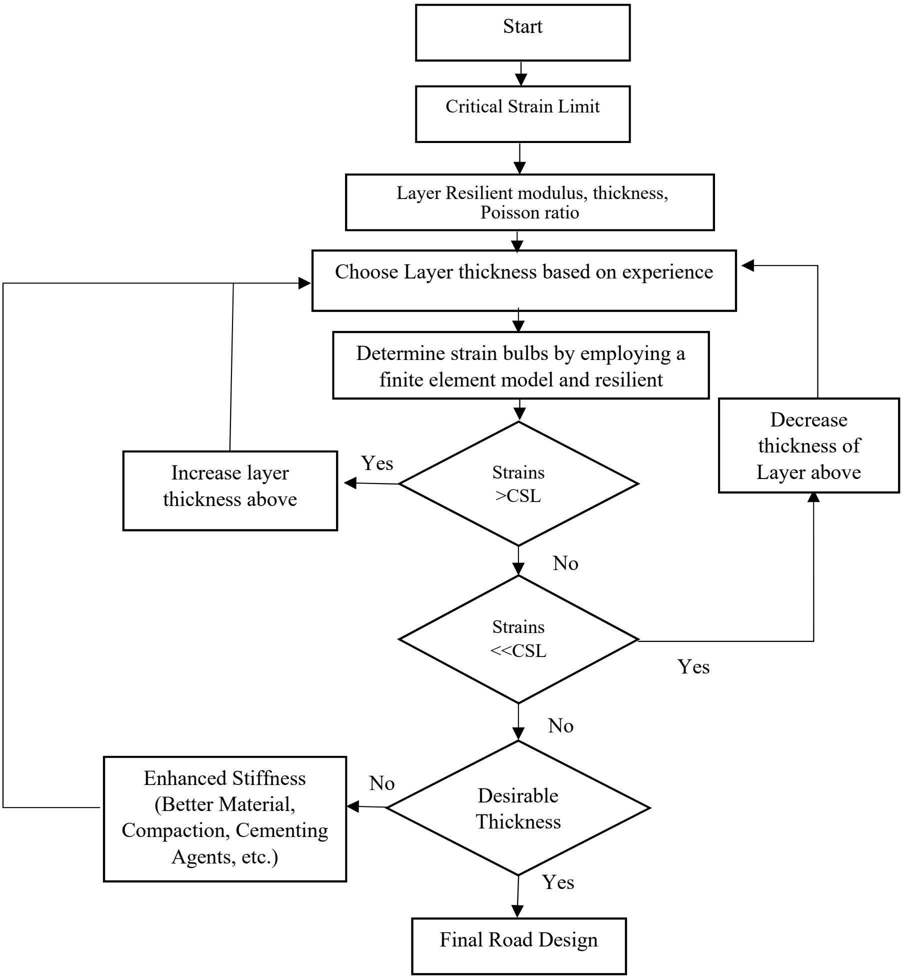


Fig. 11. Flow Diagram for a Mechanistic Design Approach

A crucial aspect of this haul road design method is the critical strain limit applicable to each layer. When the vertical strain surpasses this limit, it compromises the composite beam function of the road, leading to inadequate support for haul trucks. Research indicates different critical strain limits, roughly 1500 με at the top of the subgrade [28] and approximately 2000 με at the road surface [29]. This limit is contingent on the anticipated haul truck traffic volume over the road's operational lifespan and subsequent characteristics.

The road design in Fig. 11 uses layer-resilient moduli, ensuring vertical strain stays below the critical limit for the road's lifespan and traffic density. The critical strain limit defines how many load applications the road can handle.

Vertical strain modeling relies on the resilient modulus, which is determined through lab or deflectometer tests. It cautiously factors in Young's modulus and recoverable strain. Moisture and compaction affect it during compaction. The process involves setting a critical strain limit, evaluating layer moduli at tire contact points, computing vertical stresses, and using numerical stress analysis software. Initial layer thickness can be estimated based on similar haul road designs, prioritizing a sequence from stiffest to less stiff material to minimize vertical strain. Material characteristics, like Poisson's ratio, are crucial. Adjustments in thickness and stiffness of upper layers are needed if any layer exceeds the critical strain limit.

Step 1: A revised form of the equation used for haul roads demonstrates the correlation between the Critical Strain Limit (CSL) and factors like the design life of the roads and traffic density.

$$E = \frac{80000}{N^{0.27}} \tag{5}$$

where N represents the number of load repetitions, in this case, it is 10,00,000, and E represents Critical Strain. By substituting the value of N, the Critical Strain Limit (E) is calculated as 1919 με.

Resilient Modulus of subgrade calculated (IRC: 37-2018) [6]

$$M_{RS} = 10 \times CBR \quad \text{for} \quad \text{CBR} \leq 5 \tag{6}$$

$$M_{RS} = 17.6 \times CBR^{0.64} \quad \text{for} \quad \text{CBR} > 5 \tag{7}$$

Where M_{RS} represents the Resilient modulus of subgrade soil (in MPa) and CBR of subgrade soil (%).

Following IRC 37 (2018) Codal provision, the GSB and base layer's resilient modulus can be determined using Eq. (7).

$$M_{RG} = 0.2 \times h^{0.45} \times M_{RS} \tag{8}$$

Where

M_{RG} – Resilient Modulus of Granular Subbase Layer (in MPa),
M_{RS} – Resilient modulus of subgrade soil (Supporting Layer) (in MPa),
h – Thickness of Granular Layer (in mm).

Step 2: In this example, subgrade having a CBR of 5% is assumed, and the Resilient Modulus (M_{RS}) can be calculated using the Eq. (5):

$$M_{RS} = 10 \times 5 = 50 \text{ MPa}$$

Step 3: Based on the expertise or by performing many trials, the thickness of the GSB and base layers are selected based on Eq. (8). In this example, the GSB and base Layer thicknesses are 400 mm and 450 mm, respectively. After solving Eq. (8), the resilient modulus of the granular subbase was obtained as 148.22 MPa, and the resilient modulus of the granular base was 463.34 MPa.

Step 4: Analyse the pavement by using IITPAVE with the following inputs, elastic moduli: 736.08 MPa, 463.34 MPa, 148.22 MPa, 50 MPa having Poisson's ratio values of 0.35 for the Surface, base and GSB layers, and 0.4 for Subgrade layer – computed vertical compressive strain as 1238 $\mu\varepsilon$ < limiting strain of 1919 $\mu\varepsilon$.

IITPAVE:

IITPAVE software is a specialized tool for analyzing linear elastic layered pavement systems. It helps engineers determine stresses, strains, and deflections within a pavement under uniformly distributed single-load conditions. The software offers flexible input formats, such as contact pressure and contact area radius, wheel load, and contact pressure, or wheel load and radius of contact area, facilitating accurate pavement analysis.

For precise results, IITPAVE requires specific input values for elastic properties (e.g., elastic/resilient moduli and Poisson's ratio) of each pavement layer, excluding the subgrade. Layer thicknesses, excluding the subgrade, must also be provided. While the software handles up to ten layers, including the subgrade, a different approach is used for cases exceeding ten layers. IITPAVE is essential for designing and evaluating complex pavement systems in various engineering projects. Input and output data from the IITPAVE software are presented in TABLE 6 for reference. In this investigation, haul roads are configured for 10 million standard axles (msa) loading cycles, employing an 80% reliability level for performance rutting in accordance with IRC 37-2018 [6], allowing for a 20% margin of error in the pavement section.

TABLE 6

Representing the input and output parameters for the mechanistic method in IITPAVE

Input Parameter for IITPAVE software		**Output parameters and their values**	
Parameter	**Values**	**Parameter**	**Values**
Number of layers Tyre pressure	4 0.7 MPa	At the top of the subgrade, vertical compressive strain	1238 $\mu\varepsilon$
Poisson's ratio: • Wearing course, Base, and GSB layers • Subgrade	 0.35 0.4	Deflection (at surface)	4.10 mm
Layer thicknesses (as per designed calculations)			
Resilient moduli (calculated as per specifications as per IRC 37 Codal provision for mechanistic design)			
Wheel load	227180 N		

4.6. Method VI: Design based on mechanistic reinforced approach

Haul roads face substantial stresses and heavy loads from mining vehicles, resulting in issues like rutting, deformation, and frequent maintenance. To address these challenges, stabilizing or reinforcing techniques are incorporated into haul road design – reinforced pavement design shares similarities with unreinforced pavement design. However, the enhanced elastic modulus of the reinforced pavement layer is adjusted based on the Layer Coefficient Ratio (LCR) outlined in IRC: SP:59-2019 [23]. The design approach using LCR, IITPAVE software, and a mechanistic-empirical approach assesses strains at critical points and adjusts layer thicknesses accordingly. Existing literature includes studies demonstrating a reduction in base layer thickness with the integration of geogrid reinforcement in pavements, as reported by Sireesh [19], Mamatha [30], and Pokharel [22]. These studies indicate that the inclusion of reinforcement increases the overall stiffness of the specific layer. In the LCR method, the rise in the elastic modulus of the reinforced layer is quantified by adjusting the layer coefficient of that particular layer.

This study explores one such reinforcement technique based on the LCR to design geogrid-reinforced pavement, considering appropriate values of design traffic, subgrade CBR, and LCR. Steps 1 to 4 align with the design of unreinforced flexible pavement following IRC-37-2018 [6], while steps 5 to 8 entail additional procedures specific to the design of reinforced flexible pavements by IRC: SP:59-2019 [23].

Step 1: Determine the design traffic requirements on the pavements regarding the cumulative number of million standard axles (msa).

Step 2: Determine the 90th percentile CBR of the subgrade.

Step 3: Calculate the resilient modulus of the subgrade from the Eqs. mentioned above (6) & (7) (IRC-37, 2018).

From Eq. (5): $M_{RS} = 50$ MPa.

Step 4: Based on the expertise and after performing many iterations, the GSB layer and Base layer thicknesses are selected to be 400 mm and 350 mm, respectively. From Eq. (8), the resilient modulus of GSB and base layers are 148.22 MPa and 413.79 MPa, respectively.

Step 5: Determine the layer coefficient a_2, a_3 for the granular subbase and base layer from their obtained resilient elastic modulus from the Eqs. (9) and (10) given below:

$$a_2 = (0.249 \log_{10} E_{Base}) - 0.977 \tag{9}$$

$$a_3 = (0.227 \log_{10} E_{GSB}) - 0.839 \tag{10}$$

Where E_{Base} and E_{GSB} are the resilient moduli (in psi) obtained from Eq. (9), a_2 and a_3 are the layer coefficients for the base and GSB layers, respectively.

After calculations, the obtained layer coefficients are $a_2 = 0.21$ and $a_3 = 0.14$.

Step 6: Layer coefficients are modified for the reinforced pavements by multiplying them with LCR, as shown in Eq. (11). As per studies (IRC: SP:59-2019), the range of LCR is considered in the range of 1.2 to 1.4. In this example, an LCR of 1.2 is selected based on the assumption that the materials will be used from the mine vicinity.

$$a_i' = (LCR_i \times a_i) \tag{11}$$

LCR is taken as 1.2 in this example, and a_i is the layer coefficient of the i^{th} layer.

After calculations, the modified layer coefficients of the base and GSB layer are obtained as

$$a_2' = 0.252 \quad \& \quad a_3' = 0.168$$

Step 7: The reinforced layer's improved elastic, resilient modulus is obtained by back calculating corresponding to Eqs. (8) and (9).

The modified resilient modulus is

E'_{Base} = 862.46.79 psi or 594.65 MPa and

E'_{GSB} = 27297.52 psi or 188.20 MPa.

Step 8: Improved elastic modulus is incorporated in IITPAVE to obtain the vertical strain at the top of the subgrade to satisfy the limiting strain criteria. Analyze the pavement by using IITPAVE with the following inputs, elastic moduli: 594.65 MPa, 594.65 MPa, 188.20 MPa, and 50 MPa having Poisson's ratio values of 0.35 for the Surface, base, and GSB layers, and 0.4 for Subgrade layer – computed vertical compressive strain as 1659 $\mu\varepsilon$ < limiting strain of 1919 $\mu\varepsilon$ as shown in TABLE 7. To address unexpected disruptions and uncertainties encountered in the operational setting, a margin of error of approximately 20% is factored into the mechanistic design process for haul roads, in accordance with IRC 37 (2018) [6].

TABLE 7

Representing the input and output parameters for the reinforced method in IITPAVE

Input Parameter for IITPAVE software		**Output parameters and their values**	
Parameter	**Values**	**Parameter**	**Values**
Number of layers Tyre pressure	4 0.7 MPa	At the top of the subgrade, vertical compressive strain	1659 με
Poisson's ratio: • Wearing course, Base, and GSB layers • Subgrade	 0.35 0.4	Deflection (at surface)	4.69 mm
Layer thicknesses (as per designed calculations)			
Resilient moduli (calculated as per specifications as per IRC SP: 59 Codal provisions for geosynthetic reinforced design)			
Wheel load	227180 N		

5. Comparative Analysis of the Different Methods Available for the Design of Mine Haul Roads

This study aims to compare various methods of mine haul road designs, focusing on layer thickness, deflections, and vertical strains at different depths within the layers. As discussed, the layer thickness is determined using empirical equations, design charts, and mechanistic design approaches. The IITPAVE software, a linear elastic layered pavement software developed by IIT Kharagpur, India, is employed for pavement analysis to obtain deflections and vertical strains.

5.1. Based on Layer Thickness

The Kaufman & Ault [8] formula yields thicker layers, while the reinforced approach provides thinner layers thickness. Choosing the right thickness is vital for ensuring safe haul road design, given their role in bearing substantial mining equipment loads. Fig. 12 depicts varying layer thicknesses achieved through different design methods. Percentage changes reveal that the Kaufman & Ault formula sees the highest variation in layer thickness, in contrast to the Atkinson method, where changes are minimal. Across various regions worldwide, different design methods are being adopted to construct haul road designs to their unique mining conditions.

The Kaufman & Ault [8] method yields significantly thicker layers due to modifications replicating the increased stresses from a rear dual-wheel axle at lower depths within the road layer. Using the Equivalent Single Wheel Load (ESWL) concept to estimate cover thickness, the mechanistic design approach results in thinner layers than the Kaufman & Ault formula. Conversely, the reinforced design approach features significantly reduced cover thickness, attributed to reinforcement integration in the haul road's base layer.

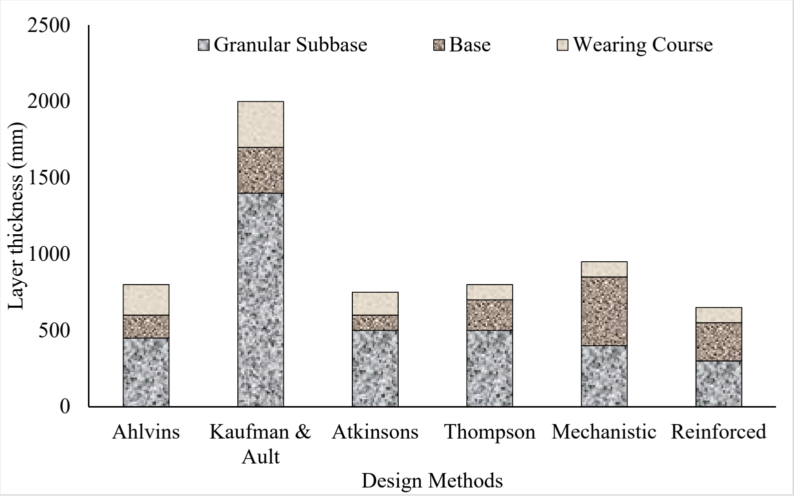


Fig. 12. Comparison of Pavement Layer Thicknesses from Different Design Methods

Using the Ahlvin [7] method as a reference from Fig. 12, the percentage change in the Kaufman & Ault [8] method was 150% higher. In contrast, the Atkinson method showed a 6.25% reduction, and the mechanistic design approach displayed an 18.75% increase. However, in the case of the reinforced approach, there was an 18.75% decrease. Interestingly, no significant change was observed with the Thompson design chart approach. This analysis indicates that the most cost-efficient option in terms of pavement thickness is the reinforced design approach. While this approach involves the cost of reinforcing materials, it is still lower than that of reduced-thickness material.

5.2. Based on Deflections and Vertical Strains

Haul roads are typically designed for the long term to ensure their durability and effectiveness over an extended operational period. This approach aims to create a robust infrastructure that can withstand the demands of continuous heavy traffic and varying environmental conditions over an extended period. Choosing the appropriate haul road design based solely on layer thickness is unreliable, as excessive thickness may lead to uneconomical solutions. In contrast, insufficient thickness could compromise driver safety and vehicular damage. Factors like deflections and vertical strain are considered in this study for further analysis to ensure the appropriate selection of haul road design. Using the IITPAVE software, Figs. 13 and 14 represent the deflections and vertical strains at the surface of the haul roads and the top of the subgrade. These additional parameters provide valuable insights for making informed decisions on the most appropriate and efficient haul road design.

The current study adopts a consistent approach of using four layers for all mine haul road design methods, including empirical, design charts, and mechanistic and reinforced design approaches. The elastic modulus for the top layer is 150 MPa (modulus of elasticity of crushed stone is 150-300 MPa), as it lies in the range of modulus value of crushed stone (www.pavementinteractive.org). The Base layer and Granular Subbase (GSB) layer are assigned elastic moduli of 250 MPa and 150 MPa, respectively, following guidelines provided by Tennant [12]. Additionally, the subgrade is set with a minimum required modulus value of 50 MPa by IRC-37 (2018) [6] specifications.

Allowable deflection at the road surface is less than 8.3 mm and 4.3 mm at the subgrade for a truck capacity of less than 240 t [16]. Limiting strain allowed for a typical haul road based on the field observation, and maximum vertical strain has been established to be 1500 to 2000 με [29,30].

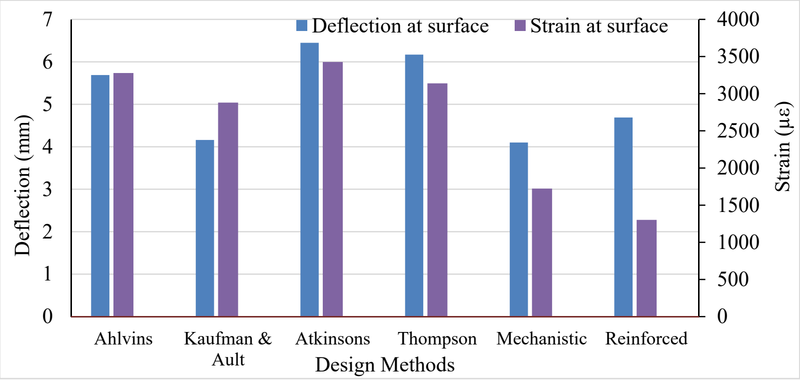


Fig. 13. Representing Deflections and Vertical Strain at the Surface of the Haul Roads

From Fig. 13, it becomes clear that the highest strains observed on the surface of the haul road fall within the range of 2800 to 3500 με, with the exceptions of the mechanistic and reinforced design approaches, which record 1723 and 1302 με, respectively. Additionally, deflections range from 5 to 7 mm, except for the Thompson formula, mechanistic and reinforced design methods, which account for 4.16 mm, 4.1 mm, and 4.69 mm, respectively.

Compared to other design methods, the mechanistic and reinforced design approaches produce superior results, highlighting the efficiency of geosynthetics in decreasing strains and deflections on the haul road surface.

In Fig. 14, variations in vertical strain levels are evident at the top of the subgrade among different design approaches. Atkinson's [9] approach recorded the highest strain at 3650 με, while Kaufman & Ault's [8] empirical formula design method had the lowest at 645 με. The mecha-

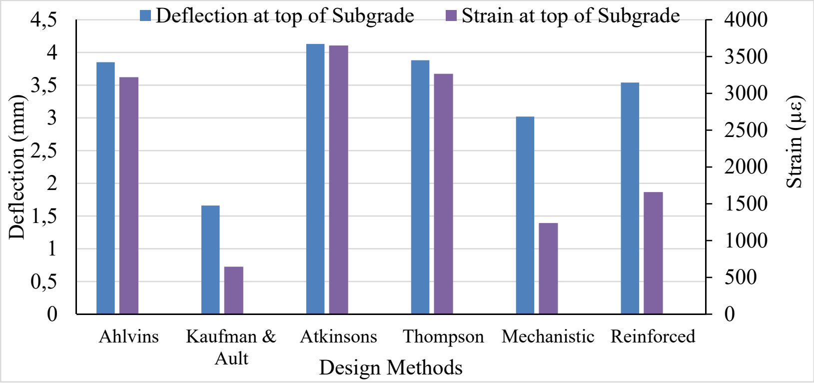


Fig. 14. Representing Deflections and Vertical Strain at the Top of the Subgrade

nistic design approach set a critical strain limit at 1919 με, with only three methods meeting this criterion: Kaufman & Ault's [8] empirical formula, mechanistic design, and reinforced design. All design methods fall within the deflection range of 1.5 to 4.5 mm, satisfying the permissible deflection of up to 5 mm [12]. From the above analysis, it is emphasized that mechanistic design and reinforced-based design methods can be suitable for practical implications. Further, using these techniques not only reduces the thickness of layers but also satisfies the critical strain limit criteria.

Kaufman & Ault's [8] formula approach achieved lower vertical strains due to its substantial 2000 mm cover thickness, though this thickness is economically not suggestible. Mechanistic and reinforced designs are recommended among the other methods due to their more reasonable layer thicknesses. The reinforced design features a 650 mm cover thickness, while the mechanistic approach has a thicker 950 mm cover, marking a 46.5% difference. However, the reinforced design involves additional costs for installing reinforcing materials during construction, which is expected to be more cost-effective than the extra thickness needed for the mechanistic approach [31]. Furthermore, it may lower maintenance and operational delay costs than other methods.

This study focused on assessing the vertical strains at various depths of the haul road for the design methods discussed earlier. Fig. 15 illustrates the vertical strains at different pavement layers, and these values were compared with the critical strain limit calculated using Eq. (6). Analyzing Fig. 15, it becomes evident that only two methods meet the critical strain limit criteria: the mechanistic design approach and the reinforced design approach. Interestingly, the Kaufman & Ault formula satisfies the critical strain limit at the top of the subgrade. However, it is not recommended due to its excessive layer thickness, which would be economically impractical. The other methods need to meet the critical strain limit criteria. Fig. 15 clearly shows a significant difference at a thickness of 500 mm between the Atkinson and Mechanistic design methods. The variation occurs because the Mechanistic design method calculates the resilient modulus for each layer based on the previous layer. However, the Atkinson method determines layer thickness from a design chart using assumed modulus values that satisfy minimal criteria for each layer. The substantial variations in layer thickness and modulus values contribute to a significant change in strain values at the 500mm thickness. Therefore, it is not advisable to utilise these methods for construction. The resulting haul roads shall incur higher maintenance costs if they are still being used, thereby making them less relevant to practical applications.

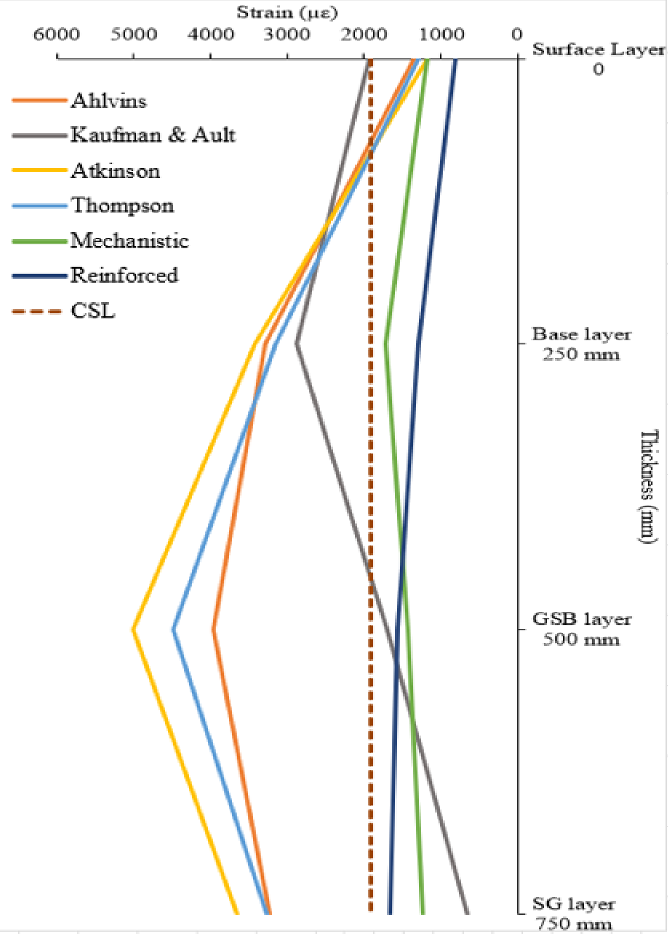


Fig. 15. Representing Vertical strains at the various layers of the haul roads

6. Conclusions

This research examines and assesses different existing haul road designs through established design methods, evaluating their design parameters using the IITPAVE software. The pavement design incorporates standard truck specifications and subgrade conditions, utilizing various existing haul road design methods. An illustrative example of one typical pavement cross-section is presented for each construction method. The research extended beyond layer thicknesses and encompassed deflections and vertical strains at different layers of the haul roads. Initially, layer thicknesses are determined using diverse design methods. Subsequently, IITPAVE software for in-depth analysis is employed to calculate vertical strains and deflections for each design method at different layers.

The findings demonstrate that the vertical strain at the top of the subgrade for mechanistic and reinforced design approaches, having 1238 με and 1659 με, respectively, effectively meets the critical strain limit having 1919 με. This success can be attributed to incorporating elastic material properties in mechanistic design calculations, facilitating efficient stress transfer between grains, and ensuring material resilience. Consequently, these approaches mitigate pavement distress, including cracking, rutting, and excessive settlement.

Conversely, based on empirical and design chart approaches provide layer thickness estimates but raise concerns regarding operational safety and cost efficiency. Kaufman & Ault's empirical approach yielded an uneconomical layer thickness of 2 m, resulting in higher operational expenses than mechanistic design. Conversely, Ahlvin, Atkinson, and Thompson's design chart methods resulted in leaner pavement thicknesses of 0.8 m, 0.75 m, and 0.8 m, respectively, but did not meet the critical strain limit criteria. Consequently, these methods are associated with elevated operational costs and maintenance expenses, especially under heavy axle loads.

Considering the critical importance of mining operations, a judicious design method is essential. Mechanistic and reinforced design methodologies offer reduced overall thickness, having 0.85 m and 0.75 m, respectively, without compromising structural integrity, even under substantial axle loads. Our study underscores the merits of these approaches, as they prioritize material properties, effectively reduce potential distress, and ensure both safety and cost-effectiveness. Compared to previously discussed pavement design methods, the reinforced design approach achieves lower overall thickness while maintaining structural robustness. This approach successfully aligns with critical strain limit criteria by accounting for material elasticity, enhancing stress distribution efficiency, and promoting resilient pavement performance. Therefore, the inclusion of reinforcement increases strength, reduces maintenance expenses, and decreases pavement thickness, resulting in lower material costs.

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References

[1] Ministry of Coal, Government of India [Internet]. coal.nic.in. Available from: https://coal.nic.in/en/about-us/history-background

[2] India's Mining Sector: Towards a Sustainable and Equitable Future [Internet]. www.teriin.org. Available from: https://www.teriin.org/article/indias-mining-sector-towards-sustainable-and-equitable-future

[3] Ministry of Coal Production and annual consumption of coal in the country [Internet]. 2023 [cited 2023 Jun 11]. Available from: https://coal.nic.in/sites/default/files/2023-03/PIB1908840.pdf

[4] S.R. Mallick, M.K. Mishra, Evaluation of clinker stabilized fly ash-mine overburden mix as sub-base construction material for mine haul roads. Geotechnical and Geological Engineering **35**, 1629-44 (2017).

[5] M. Saberian, M.M. Khabiri, Experimental and numerical study of the effects of coal on pavement performance in mine haul road. Geotechnical and Geological Engineering **35**, 2467-78 (2017).

[6] IRC S. 37 (2018) Guidelines for the design of flexible pavements. In Indian Road Congress New Delhi 2018.

[7] R.G. Ahlvin, Multiple-wheel heavy gear load pavement tests. Army Engineer Waterways Experiment Station; 1971.

[8] W. W. Kaufman, J. C. Ault, The design of surface mine haul roads manual. USDOI Information Circular **8758**, 2-7 (1977).

[9] T. Atkinson, Design and layout of haul roads. SME Mining Engineering Handbook **2**,1334-42 (1992).

[10] R.J. Thompson, A.T. Visser, Mining Roads, Mine Haul Road Design, Construction & Maintenance Management (2011).

[11] R.J. Thompson, A.T. Visser, Towards a mechanistic, structural design method for surface mine haul roads. Journal of the South African Institution of Civil Engineers **38** (2), 13-20 (1996).

[12] D. Tannant, B. Regensburg, Guidelines for mine haul road design (2001).

[13] B.A. Wills, Developments in mineral processing. Mine Quarry (United Kingdom) **1**, 18 (3) (1989).

[14] L.W. Van Wieren, H.M. Anderson, An overview of haul roads at Syncrude Canada Limited. InProc. 2nd Int. Symp. Mining Planning and Equipment Selection 283-289 (1990).

[15] R. Cameron, R. Mahood, R. Lewko, J. Skitmore, Haul road investigation of problem areas for 240-T heavy haulers driving on 170-T haul road design at Syncrude Canada Limited. Internal Report. Syncrude Canada Limited, (1995).

[16] R. Cameron, R. Mahood, R. Lewko, J. Skitmore, Haul road design, construction, and monitoring procedures for 240-T heavy haulers at Syncrude canada Limited. Internal Report. Syncrude Canada Limited (1996).

[17] R.J. Thompson, A.T. Visser, Management of unpaved road networks on opencast mines. Transportation research record, **1652** (1), 217-224 (1999).

[18] M. Verma, I. Roy, U.C. Sahoo, Design of Haul Roads in Open Cast Mines in India – A Mechanistic Design Approach. Journal of The Institution of Engineers (India): Series D **101**, 285-301 (2020).

[19] S. Saride, R. Baadiga, U. Balunaini, M.R. Madhira, Modulus improvement factor-based design coefficients for geogrid-and geocell-reinforced bases. Journal of Transportation Engineering, Part B: Pavements **1**, 148 (3), 04022037 (2022).

[20] R. Baadiga, S. Saride, U. Balunaini, M.R. Madhira, Influence of tensile strength of geogrid and subgrade modulus on layer coefficients of granular bases. Transportation Geotechnics **29**, 100557 (2021).

[21] J. Han, S.K. Pokharel, X. Yang, C. Manandhar, D. Leshchinsky, I. Halahmi, R.L. Parsons, Performance of geocell-reinforced RAP bases over weak subgrade under full-scale moving wheel loads. Journal of Materials in Civil Engineering **23** (11), 1525-1534, (2011).

[22] S.K. Pokharel, J. Han, D. Leshchinsky, R.L. Parsons, I. Halahmi, Behavior of geocell-reinforced granular bases under static and repeated loads. In Contemporary topics in ground modification, problem soils, and geo-support 409-416 (2009).

[23] IRC S. 59: Guidelines for use of geosynthetics in road pavements and associated works. In The Indian Road Congress, New Delhi 2019.

[24] India. Ministry of Road Transport & Highways. Specifications for road and bridge works. Indian Roads Congress, 2013.

[25] Granular Sub Base Construction And Quality Control | Construction Civil [Internet]. Construction Civil. 2020 [cited 2023 Apr 17]. Available from: https://www.constructioncivil.com/granular-sub-base-construction-quality-control/#gsc.tab=0

[26] *Volvo-FMX-500-8x4*. Volvo Trucks; Volvo Group. [cited 2023 Jul 03]. Available from: https://www.volvotrucks.in/content/dam/volvotrucks/markets/india/transportneeds/Volvo-FMX-500-8x4.pdf.

[27] Global Energy Monitor. Umrer Coal Mine – Global Energy Monitor [Internet]. Global Energy Monitor. Global Energy Monitor; 2024 [cited 2023 Jul 27]. Available from: https://www.gem.wiki/Umrer_Coal_Mine

[28] Elastic Modulus – Pavement Interactive [Internet]. Available from: https://pavementinteractive.org/reference-desk/design/design-parameters/elastic-modulus/

[29] J.R. Morgan, J.S. Tucker, D.B. McInnes, A mechanistic design approach for unsealed mine haul roads. In17TH Arrb Conference, Gold Coast, Queensland, 15-19 August 1994, Proceedings **17**, PART 2, (1994).

[30] R.J. Thompson, 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).

[31] K.H. Mamatha, S.V. Dinesh, Performance evaluation of geocell-reinforced pavements. International Journal of Geotechnical Engineering **4**, 13 (3), 277-86 (2019 May).