

Toward Context-Sensitive Rigid Pavement Design in Indonesia: Insights from MDPJ 2024

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Abstract Rigid pavements are essential for Indonesia's transportation infrastructure, where large variations in subgrade conditions and traffic loading pose significant design challenges. The recently released Indonesian Road Pavement Design Manual (MDPJ) 2024 provides updated procedures for rigid pavement design; however, the sensitivity of its design outcomes to the key input parameters has not yet been critically evaluated. This study investigated the influence of subgrade strength, concrete flexural strength, and regional axle load distribution on rigid pavement thickness using the MDPJ 2024 framework. A parametric analysis was conducted by varying the subgrade CBR values, concrete flexural strengths, and representative traffic characteristics for Java, Sumatra, and Kalimantan. The pavement performance was assessed using fatigue and erosion criteria. The results show that erosion consistently governs the design, whereas variations in concrete flexural strength have a negligible influence on the slab thickness. Subgrade strength and regional axle load distribution significantly affect the required pavement thickness, with heavier traffic conditions in Java resulting in thicker slabs than those in other regions. These findings highlight the importance of erosion-focused design and region-specific traffic considerations for optimising rigid pavement design under MDPJ 2024.

Keywords Axle Load Distribution, Erosion and Fatigue Analysis, Pavement Design Manual, Rigid Pavement, Subgrade

1. Introduction

In Indonesia, the construction and upkeep of reliable road infrastructure are important factors for economic growth, and the country's road connectivity must be improved to achieve this. Indonesia is also unique in that the mainland is composed of several different and varied mainland geotechnical regions and has road traffic that varies greatly [1-4]. Of the several different types of road systems that are available, rigid pavement systems are the most important in road construction and maintenance since they are able to bear heavy loads of traffic, have long life spans, and have lower maintenance costs than flexible pavements [5-7]. These factors are why rigid pavements are most used on heavily congested road corridors, access roads to ports, toll roads, and industrial areas where road structural integrity and continuous servicing are most needed [8-12].

However, considerable attention must be paid to the challenges posed by rigid pavement design. One of the most pressing of these issues is the variable subgrade conditions due to the country's diverse geological features [13-16]. Subgrade formulations, especially the California Bearing Ratio (CBR), directly affect the required pavement thickness and overall structural integrity of the pavement, given the soft organic soils in the coastal and swampy areas

and the lateritic and volcanic soils in the inland region [17-19]. Apart from the geotechnical context, there are also considerable differences in traffic loading conditions in various areas [20-22]. In towns, the traffic is mixed and includes considerable volumes of heavy vehicles, whereas in more remote or rural areas, the traffic is sparse and light, and the road still needs to be robust because of the limited maintenance it is likely to receive. This calls for pavement design that is not only sound in structure, but also flexible for the stated local conditions [23-27].

To enhance the quality and consistency of road pavement designs nationwide, the Indonesian Ministry of Public Works and Housing put forth the 2024 Road Pavement Design Manual (MDPJ) [28]. This edition is the new national standard reference for pavement design, considering new developments in pavement engineering, traffic analysis, and material behaviour for flexible and rigid pavements. For rigid pavement systems, MDPJ 2024 outlines detailed steps for calculating the slab thickness in relation to the subgrade strength (CBR), design traffic volume, and concrete grade. Although the outlined steps form a strong basis, the diverse conditions in Indonesia call for further analysis of the practical usability of these steps, particularly in terms of design sensitivity to geotechnical and material variations.

Prior research on the design of rigid pavements has shown that subgrade characteristics, materials, and traffic loading have lasting effects on their performance and life. For example, Thompson and Dempsey [29] reinforce the idea that subgrade conditions vitally affect the performance and life of pavement systems. Their study detailed how the strength and deformation of subgrade soil (especially clay content and plasticity) are influenced by water content, temperature, and soil composition. A particularly important point is the resilient modulus, which measures the soil's ability to recover from deformation and is a key determinant of pavement performance. This study reviews how environmental conditions impact the terrain, particularly how moisture and heat affect subgrade shifting. This study reached a design approach for the factors to be considered in the subgrade design to predict the performance of pavements under challenging conditions, with the environmental factors being the most variable and challenging.

Along similar lines, Al-Jhayyish and Sargand [30] analyzed the effect of stabilising the subgrade on the stiffness and performance of pavements. They performed FWD and PSPA in situ tests on 20 pavement sections in Ohio, USA. The collected data allowed the estimation of the stiffness (moduli) of the pavement layers, which were validated through finite element analysis in ABAQUS [31]. These validated figures were instrumental in determining the structural numbers and layer coefficients of pavements. The findings indicate that subgrade stabilisation can decrease the pavement thickness required and help lower surface distress, demonstrating the positive impact of design efficiency and pavement durability.

Several assessments related to the Indonesian context have referenced older national guidelines like Pd T-14-2003 [32] or MDPJ 2017 [33] and have focused on evaluating the pavement design results considering the soil and traffic conditions. Despite these efforts, previous studies have focused on several inconsistent assumptions and have not made comparisons on a regional scale. MDPJ 2024 was recently published, but most of the literature concerning its developed rigid pavement design still lacks critical academic analysis, particularly how it tackles Indonesia's diverse geotechnical and climatic zones. Furthermore, very few studies have sufficiently changed the key parameters of the CBR, concrete strength, and location to evaluate design results.

Although the MDPJ 2024 represents a major update in Indonesia's rigid pavement design practice, there is currently a lack of academic studies that critically evaluate its design sensitivity to key input parameters. Most existing Indonesian pavement studies are based on earlier guidelines, such as Pd T-14-2003 or MDPJ 2017, and generally adopt fixed assumptions regarding subgrade strength, concrete properties, and traffic loading. Consequently, the extent to which variations in the subgrade CBR, concrete flexural strength, and regional axle load distribution influence the rigid pavement thickness under the MDPJ 2024 framework remains unclear. In particular, no prior study has systematically examined whether fatigue or erosion governs design outcomes across different regions in Indonesia using updated procedures. This knowledge gap raises important questions regarding the applicability and optimisation potential of MDPJ 2024 for diverse geotechnical and traffic conditions.

To address this gap, this study performed a parametric evaluation of rigid pavement designs based on MDPJ 2024 by systematically varying the subgrade CBR, concrete flexural strength, and regional axle load distributions representative of Java, Sumatra, and Kalimantan. This study aims to identify the governing design mechanisms and assess the sensitivity of pavement thickness to these parameters, thereby providing practical insights for region-specific and erosion-focused rigid pavement designs in Indonesia. Although the MDPJ 2024 serves as the national framework for Indonesia, its design philosophy aligns with the global mechanistic-empirical rigid pavement design principles. Therefore, evaluating its sensitivity to subgrade and traffic parameters contributes not only to national implementation but also to broader discussions on erosion-dominated rigid pavement performance under varying traffic spectra.

2. Rigid Pavement Design Procedure Based on MDPJ 2024

The Road Pavement Design Manual (MDPJ) 2024 outlines the design of rigid pavements with detailed and uniform instructions. The methods in the manual

incorporate both empirical formulae and mechanistic methodologies to derive the slab thickness from the subgrade strength, concrete properties, and anticipated traffic volumes. In this section, the slab design methodologies in MDPJ 2024 are reviewed, with a focus on providing the foundation for the parametric evaluation in this study.

The design of rigid pavements incorporates a mix of empirical formulas and mechanistic analyses to guarantee that the pavement performance is suitable for the anticipated traffic load and climate conditions. The design procedure calculates the expected total number of commercial vehicle axles for the design life of the pavement (*JSKN*) using the following equation:

$$JSKN = (\sum LHR_{JK} \times JSKN_{JK}) \times 365 \times DD \times DL \times R \quad (1)$$

$$R = \frac{(1+0.01i)^{UR}-1}{0.01i} \quad (2)$$

where *LHR_{JK}* is the average daily traffic of each type of commercial vehicle (vehicles/day), *JSKN_{JK}* is the axle per vehicle type, *DD* is the directional distribution factor, *DL* is the lane distribution factor, *R* is Growth factor for cumulative traffic volume, *UR* is the design life (years), and *i* is the annual traffic growth rate (%).

Based on the calculated *JSKN*, the appropriate subbase type and thickness were selected from Table 1.

Table 1. Minimum thickness of the subbase layer

JSKN	Subbase layer
< 10 ⁶	CTB 125 mm
10 ⁶ – 5 x 10 ⁶	LC 100 mm or CTB 150 mm
5 x 10 ⁶ – 1 x 10 ⁷	LC 125 mm
>1 x 10 ⁷	LC 150 mm

CTB: Cement Treated Base, LC: Lean Concrete

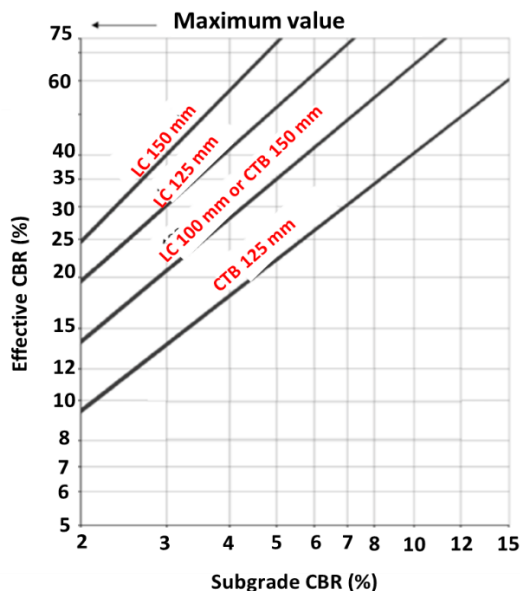


Figure 1. Effective CBR

Following subbase selection, the effective CBR of the subgrade (*E_f*) was determined using Figure 1, which considers the original subgrade CBR and the influence of the selected subbase. The effective CBR is a critical parameter in rigid pavement design that represents foundation stiffness.

The next step involved determining the material properties of the rigid pavement system, with particular emphasis on the flexural strength of concrete. According to MDPJ 2024, rigid pavements should use concrete with a minimum flexural strength of *f_{cf}* = 4.5 MPa to ensure adequate resistance against tensile stresses induced by wheel loading and temperature gradients. The required slab thickness *D* (mm) was determined through an integrated evaluation of the fatigue and erosion performances. These evaluations require the calculation of the equivalent stress *S_e* (MPa) and erosion factor *F_e*, which are expressed in MDPJ 2024 using the following empirical equations:

$$S_e \text{ atau } F_e = a + \frac{b}{D} + c \ln E_f + \frac{d}{D^2} + e(\ln E_f)^2 + f \frac{\ln E_f}{D} + \frac{g}{D^3} + h(\ln E_f)^3 + i \frac{(\ln E_f)^2}{D} + j \frac{\ln E_f}{D^2} \quad (3)$$

where *D* is the concrete slab (mm), and *E_f* is the effective subgrade CBR (%).

The coefficients *a – j* for the calculation of *S_e* and *F_e* depend on the axle and wheel configurations and are provided in Tables 2 and 3, respectively, as specified in MDPJ 2024.

Table 2. Coefficient of equivalent stress (*S_e*)

Coefficient	STRT & STdRT	STRG	STdRG	STrRG
a	-0.051	0.33	0.088	-0.145
b	26	206.5	301.5	258.6
c	0.0899	-0.4684	-0.1846	0.008
d	35774	28661	4418	1408
e	-0.0376	0.165	0.0939	0.0312
f	14.57	2.82	-59.93	-61.25
g	-861548	-686510	280297	488079
h	0.0031	-0.0186	-0.0128	-0.0058
i	1.3098	-1.9606	4.1791	4.7428
j	-4009	-2717	1768	2564

STRT: single axle, single wheel

STdRT: double axle, single wheel

STRG: single axle, double wheel

STdRG: double axle, double wheel

STrRG: triple axle, double wheel

Table 3. Coefficient of erosion factor (F_e)

Coefficient	STRT	STRG	STdRG & STdRT	STrRG
a	0.345	0.914	1.564	2.104
b	534.6	539.8	404.1	245.4
c	-0.1711	-0.1416	-0.1226	-0.2473
d	-44908	-44900	-32024	-15007
e	0.0347	0.0275	0.0256	0.0469
f	20.49	16.37	-9.79	8.86
g	1676710	1654590	1150280	518916
h	-0.0038	-0.0032	-0.0052	-0.0075
i	-1.3829	-0.9584	2.1997	1.5517
j	-913	-765	469	-599

The allowable number of load repetitions for fatigue (N_f) and erosion (N_e) was computed using the following expressions:

$$\log_{10} N_f = \left(\frac{0.9719 - S_r}{0.0828} \right) \quad \text{If } S_r > 0.55 \quad (4)$$

$$N_f = \left(\frac{4.258}{S_r - 0.4325} \right)^{3.268} \quad \text{If } 0.45 \leq S_r \leq 0.55 \quad (5)$$

$$N_f = \text{unlimited} \quad \text{If } S_r < 0.45 \quad (6)$$

where S_r is defined as:

$$S_r = \frac{S_e}{0.944 f_{cf}} \left(\frac{P L_{sf}}{4.45 F_1} \right)^{0.94} \quad (7)$$

The allowable number of erosion repetitions (N_e) is calculated as follows:

$$\log_{10}(F_2 N_e) = 14.524 - 6.777 \left[\max \left(0, \left(\frac{P L_{sf}}{4.45 F_4} \right)^2 \frac{10^{F_3}}{41.35} - 9 \right) \right]^{0.103} \quad (8)$$

where F_2 is the adjustment factor that accounts for the effect of the shoulder type on erosion susceptibility at the slab edges, taken as 0.94, as defined in MDPJ 2024 for slabs with non-concrete (unbound) shoulders. P is the axle load (kN), f_{cf} is the concrete flexural strength (MPa), L_{sf} is the load safety factor (taken as 1.2), and F_1 and F_4 are axle configuration coefficients defined in MDPJ 2024, which are dependent on the axle grouping and wheel configuration determined using Table 4.

Table 4. Coefficient for N_f and N_e

Axle	F1	F4
STRT	9	9
STRG	18	18
STdRT	18	18
STdRG	36	36
STrRG	54	54

Finally, the cumulative design axle repetitions (JSKN) were compared with the calculated allowable fatigue and

erosion capacities to verify structural adequacy. This integrated fatigue–erosion framework ensures that rigid pavement designs are both structurally reliable and consistent with traffic loading and subgrade conditions that are representative of different regions in Indonesia.

3. Methods

A parametric evaluation method was used to assess the impact of subgrade strength (CBR), compressive strength of concrete, and regional traffic characteristics on rigid pavement design according to MDPJ 2024. To estimate the design traffic, this study used the axle configuration and daily traffic volume for each type of commercial vehicle, as presented in Table 5.

Table 5. Traffic data analysis

Vehicle Type	Configuration	Daily traffic
Large bus	1.2	50
2-axle light truck	1.1	50
2-axle medium truck	1.2	50
3-axle heavy truck	11.2	50
3-axle heavy truck	1.22	50
4-axle heavy truck	11.22	50
4-axle heavy truck	1.2+2.2	50
5-axle heavy truck	11.2+2.2	50
5-axle heavy truck	1.22+2.2	50
4-axle heavy truck	1.2-22	50
5-axle heavy truck	1.22-22	50
5-axle heavy truck	1.2-222	50
6-axle heavy truck	1.22-222	50

To analyse pavement performance for different axle configurations, a uniform daily traffic volume of 50 vehicles per day per vehicle type was assumed for all axle groups. This modelling choice was intentionally adopted to isolate the structural influence of the axle configuration and load magnitude within the MDPJ 2024 framework. By treating all vehicle types equally, the analysis avoids bias associated with region-specific traffic composition and enables a clearer comparison of fatigue and erosion responses across axle configurations, ranging from single-axle light vehicles to multi-axle heavy trucks. Because the fatigue and erosion formulations in MDPJ 2024 are primarily governed by axle grouping and load effects, the use of a balanced traffic input allows differences in pavement performance and required slab thickness to be directly attributed to axle type, subgrade condition, and concrete properties rather than traffic volume. However, real-world traffic distributions are typically non-uniform; therefore, the results presented in this study should be interpreted comparatively.

This study adopted a 40-year design life for rigid pavement systems, which is considered an industry standard. Such a design life is the minimum for rigid pavements to capture their long-term durability. Concrete with a flexural strength of 4.5 MPa was considered in this study. Axle configured load was determined for a particular location in Java. Moreover, an annual traffic volume increase of 2% was assumed for the design life. This assumed growth is justified for developing traffic-laden economically developing regions, which is consistent with the growth used for national transport.

Finally, to study the design of rigid pavements with site and material condition variations, this study systematically modified the three. First, the subgrade quality was represented analytically, using a Range of CBR values which were representative of weak to moderate jelly soil road conditions in Indonesia. These soil conditions are sufficiently packed to remove sufficient hold, provide sufficient effective subgrade support, and reduce the support used during the design steps. In the second case, concrete flexural strength variations were used to identify the extent to which incremental increases in concrete quality would enhance fatigue resistance and reduce the required thickness of the pavement according to the fatigue performance equations of MDPJ 2024.

In the third case, to study the impact of regional characteristics, Java, Sumatra, and Kalimantan were used as three distinct geographical locations. These zones have unique combinations of commercial vehicle activity, axle weight distributions, and weather conditions, all of which affect pavement engineering. Regional volume data for each area studied were used to determine the axle groupings for the fatigue and wear analyses. This study aims to fill this research void by clearly explaining the influence of the control of different factors, in isolation and in conjunction, on the performance of rigid pavements.

4. Results and Discussion

This subsection presents the results of a parametric study evaluating the influence of subgrade strength (CBR), concrete flexural strength, and axle load distribution across the region on the design of rigid pavements. The isolated and combined effects of these parameters on the thick pavement and the performance of the structure as a whole are detailed thematically for ease of explanation. The design output was evaluated for each proposed slab thickness and whether it passed the fatigue and erosion parameters. This study illustrates the effects of these parameters on the design of pavements in multiple scenarios and the practical challenges associated with the parametric optimisation of rigid pavements in various regions of Indonesia.

4.1. Influence of Subgrade CBR

The California Bearing Ratio (CBR) reflects the strength

of the subgrade and must be considered in the design of rigid pavement. This is due to the fact that it affects the modulus of subgrade reaction, altering the thickness of the concrete slab necessary. This study looked at 4 levels of CBR (2%, 4%, 6%, 8%, and 10%), reflecting weak to moderately strong subgrade, as is the case in most parts of Indonesia. From the cumulative axle load (JSKN) and as per MDPJ 2024, LC (lean concrete) is allowed to be used as a subbase at 2 alternative thicknesses, 125 mm and 150 mm. Consequently, a rigid pavement design was performed for each CBR value, and the slab thicknesses for both the subbase options were compared.

Figure 2 shows how the CBR value of the subgrade affects the required concrete thickness of the two subbase variants. Higher CBR subgrades can support a reduced thickness of the concrete slabs. This is true. For example, the thickness requirements for both subbase variants decreased considerably as the CBR values increased from 2% to 10%. Notably, an LC with a thickness of 150 mm had a relative advantage over an LC with a thickness of 125 mm in yielding thinner slabs at the same CBR, which reinforces the observation that an LC with a thickness of 150 mm provides greater support.

The difference in the slab thickness between the 125 mm and 150 mm thick LC slabs was more noticeable at lower CBR values. This is because the subgrade has a relatively lower load-carrying capacity, and the subbase layer becomes more important. When the CBR values were 8% or more, the difference in the thickness required for the two subbases was negligible. This indicates that as the subgrade strength improved, the difference in the type of subbase used became negligible.

Figure 3 shows the performance of each design configuration in terms of fatigue and erosion resistance. To determine the governing design criterion, the percentage utilisation of both fatigue and erosion capacities was evaluated. The results indicate that fatigue is not a controlling factor in any scenario, as evidenced by 0% fatigue utilisation across all CBR values and subbase configurations. This suggests that the selected slab thickness provides sufficient tensile capacity to resist repeated flexural stresses induced by traffic loading and that the allowable fatigue repetitions are not approached within the design life.

In contrast, the erosion criterion consistently governed the slab thickness. Within the MDPJ 2024 framework, erosion represents the progressive deterioration of support conditions at the slab-subbase interface, caused by repeated shear stresses under axle loading. Unlike fatigue, which controls cracking within the concrete slab, erosion is associated with the pumping of fine materials, void formation beneath slab edges and joints, and eventual differential settlement or joint faulting. When erosion utilisation approaches 100%, it indicates that the allowable number of erosion repetitions is nearly exhausted, implying an increased risk of long-term serviceability degradation owing to the loss of foundation support.

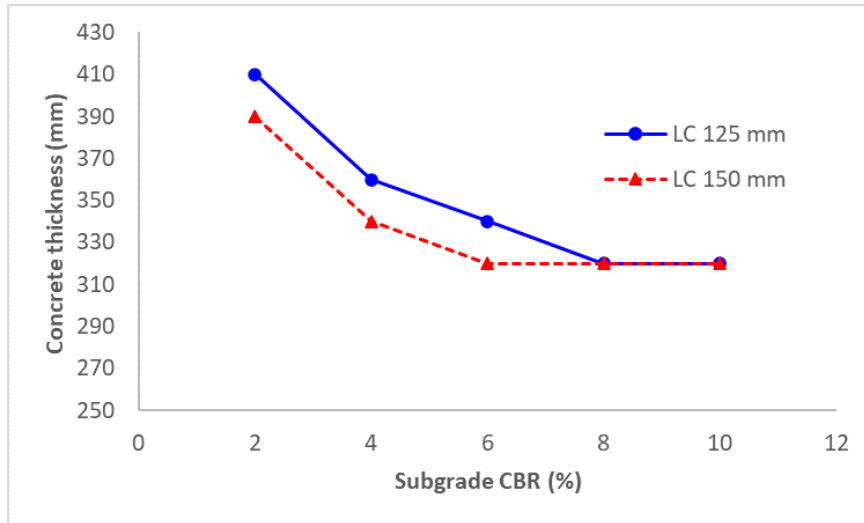
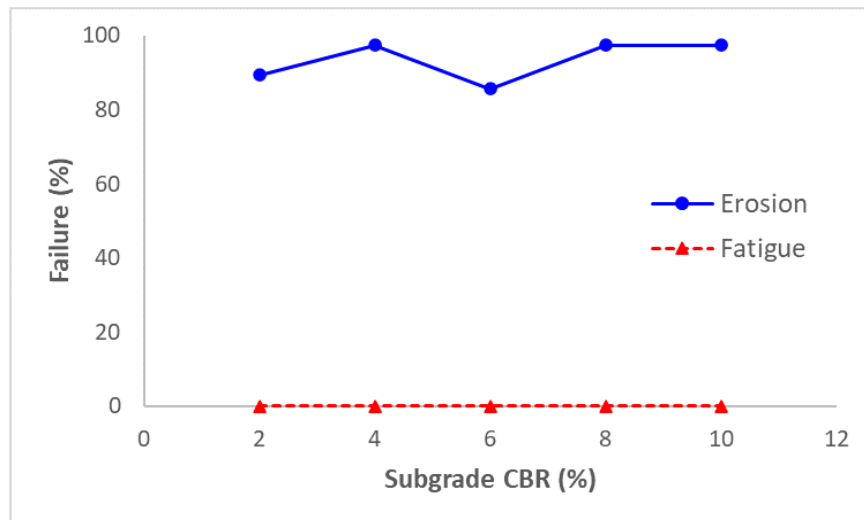
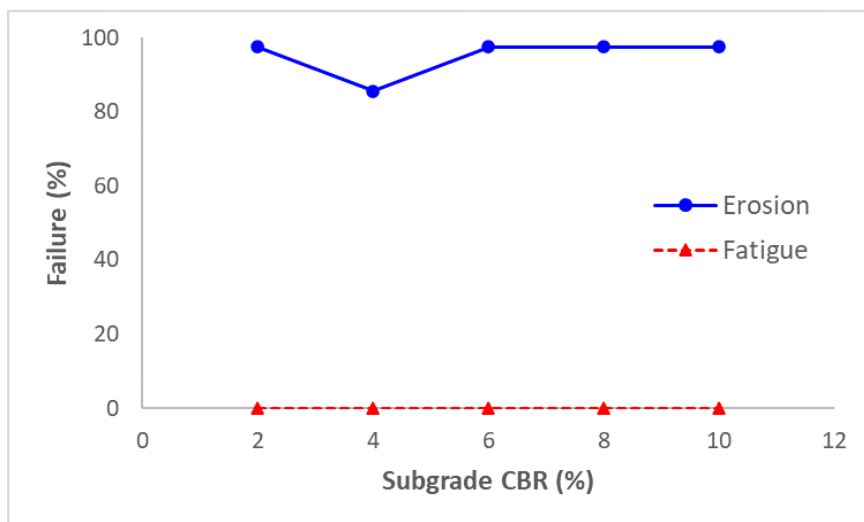


Figure 2. Pavement Thickness for Various CBR Values



a. LC 125 mm subbase



b. LC 150 mm subbase

Figure 3. Pavement Performance Utilization for Various CBR Values

The importance of erosion control is particularly evident at lower subgrade CBR values. For the 125 mm lean concrete (LC) subbase configuration, the erosion utilisation reached 89% at CBR = 2% and increased to over 95% at higher CBR levels, demonstrating that the slab thickness is predominantly determined by the need to limit shear-induced deterioration at the slab–subbase interface. A similar trend was observed for the 150 mm LC subbase, where erosion utilisation was 98% at CBR = 2% and stabilised at approximately 97% from CBR = 6% onwards. These results indicate that even when subgrade support improves, erosion remains the critical performance mechanism, reflecting the sensitivity of the slab–subbase interaction to repeated axle loading rather than solely to global slab stiffness.

In addition to evaluating the total erosion demand, this study examined the relative contribution of individual axle configurations to overall erosion utilisation. The distribution of erosion demand among axle types for the 125 mm LC subbase configuration is illustrated in Figure 4, where the contributions of STRT, STRG, STdRT, STdRG, and STrRG axle groups are presented for varying CBR levels. This breakdown enables a more detailed understanding of how specific axle configurations influence the governing mechanisms of erosion.

It was found that double axles with single wheels (STdRT) demanded the highest portion of erosion, between 61% and 68% of the total, followed by double axles with double wheels (STdRG) at 20%–24%. Conversely, single axles with double wheels (STRG) and triple axles (STrRG) contributed less than 7%, whereas single axles with single wheels (STRT) contributed an insignificant amount to the total.

The dominance of the STdRT configuration is not merely a consequence of a higher load magnitude but rather a combined effect of the wheel configuration, stress concentration, and cumulative load interaction within the slab–subbase system. In a single-wheel tandem configuration, the contact stress is more concentrated than in dual-wheel arrangements, resulting in higher localised tensile and shear stresses near the slab edges and joints. Moreover, the tandem axle spacing produces overlapping stress influence zones within the slab, increasing the magnitude and repetition of the shear stresses transmitted to the slab–subbase interface. These repeated shear actions accelerate erosion-related mechanisms, such as pumping and loss of support, particularly in pavements constructed over weaker subgrades or with thinner slabs.

Within the MDPJ 2024 erosion formulation, these mechanical effects are implicitly captured using axle-specific coefficients and nonlinear load terms, which amplify the contribution of axle configurations characterised by concentrated loading and repeated stress application. Although some axle groups may carry a greater total gross weight, dual-wheel and triple-axle systems distribute loads more effectively, reducing the stress intensity at the slab edge and consequently lowering their relative erosion contribution.

The persistence of STdRT dominance across all examined CBR levels further indicates that subgrade improvement alone does not eliminate the structural sensitivity to the axle configuration. While higher CBR values reduce the overall erosion demand, the relative contribution of STdRT remains significant because erosion is governed primarily by localised stress transfer mechanisms rather than global slab stiffness alone.

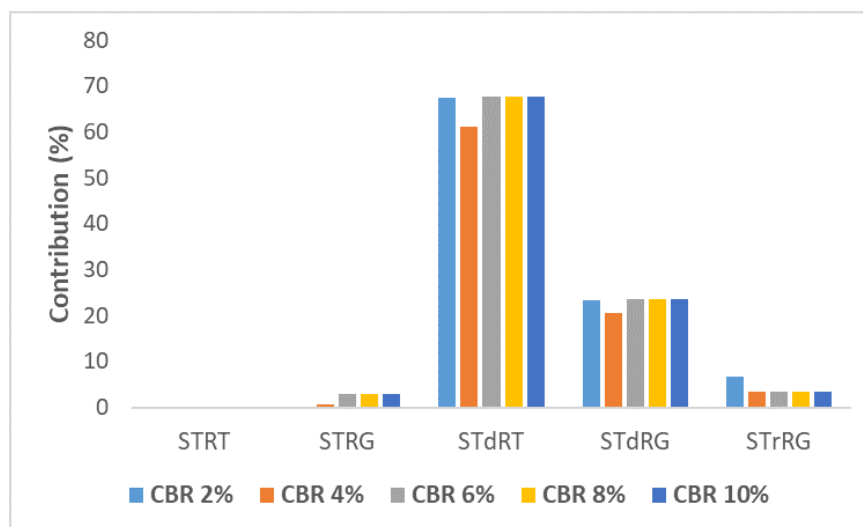


Figure 4. Percentage Contribution of Axle Load Types to Erosion Demand

From a design perspective, understanding the mechanistic basis of the axle-type erosion contribution enables more targeted optimisation strategies. Corridors with a higher proportion of STdRT traffic may require enhanced subbase stiffness, improved drainage to limit moisture-induced pumping, and increased slab thickness at critical locations, such as joints and edges. This finding reinforces the importance of incorporating axle configuration characteristics, rather than total traffic volume alone, into erosion-controlled rigid pavement design under MDPJ 2024.

Although this study was conducted within the framework of the MDPJ 2024, the observed trends are consistent with the findings of international rigid pavement design methodologies. Mechanistic–empirical approaches, such as the AASHTO and PCA design procedures, similarly recognise erosion and pumping at slab edges as critical performance mechanisms under repeated heavy axle loading. The dominant influence of tandem axle configurations with concentrated wheel loads has also been reported in international pavement research, where load repetition and stress overlap effects significantly affect the slab–subbase interaction. Therefore, while the numerical results are specific to MDPJ 2024, the mechanistic insights regarding erosion-controlled design and axle configuration sensitivity are broadly applicable to rigid pavement systems beyond Indonesia.

4.2. Influence of Concrete Flexural Strength

Flexural strength influences the structural capacity and fatigue performance of rigid pavement systems. According to the fatigue analysis in the MDPJ 2024 framework, the flexural strength of concrete (f_{cf}) also determines the minimum slab thickness required to allow repeated loading over the pavement service life. Therefore, this study assessed four fatigue flexural strengths: 4.5 MPa, 4.75 MPa, 5.0 MPa, and 5.25 MPa, which are the average strengths

that can be attained with different concrete mix designs. The analysis was performed with a subgrade CBR of 6% and a 125 mm thick lean concrete (LC) subbase to isolate the effect of concrete strength on the design results.

The analysis revealed that changes in concrete flexural strength between 4.5 MPa and 5.25 MPa did not change the thickness of the slab, which remained at 340 mm for all instances, as illustrated in Figure 5. This aligns with the previous observations in Section 4.1, where the design was governed by erosion, rather than fatigue. Because the flexural strength of concrete primarily affects fatigue resistance, its influence on the thickness of the slab is diminished when erosion is the predominant failure mode of the pavement. Therefore, in this case, there is no design economy to be gained by reducing the thickness, which is the desired design, although for long-term durability and crack control, it will still be beneficial.

Figure 6 demonstrates how different axle configurations affect erosion performance. The data indicate that the contributions of different axle types remain consistent regardless of the flexural strength level. In terms of erosion impact, the STdRT axle group had the largest contribution (67.65 %), followed by STdRG (23.60 %). STRG and STRG made smaller contributions of 2.88% and 3.36%, respectively. The STRT axle group had an insignificant impact in all scenarios, consisting of 0.00%.

The uniformity here indicates that the flexural strength has no effect on the type or ratio of the erosion demand caused by variable axle loads. Erosion, which is related to slab edge loading and the interaction of the subbase with the pavement, is primarily driven by the slab material properties. The key point is that erosion is largely driven by the configuration and frequency of the load applied. The dominance of double-axle single-wheel loads (STdRT) shows that erosion can be significant, even with high-strength concrete. This highlights the need to consider this axle type as a structural element in pavement engineering studies.

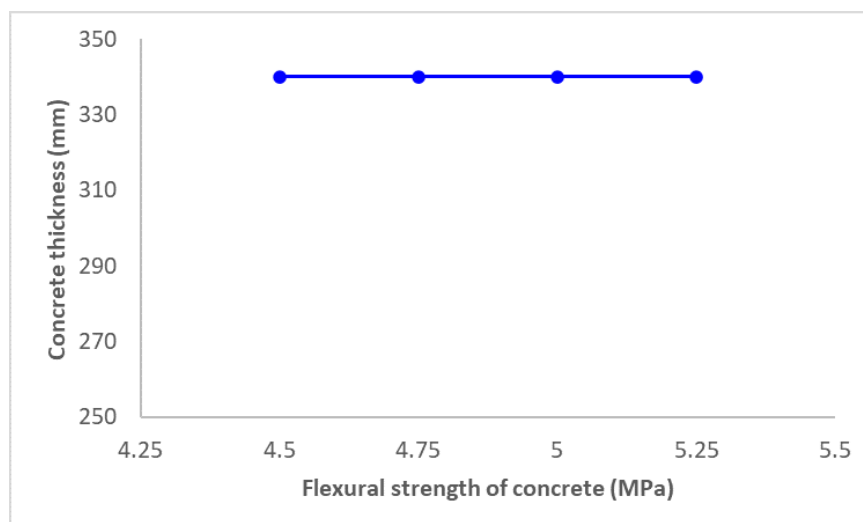


Figure 5. Pavement Thickness for Various Flexural Strengths of Concrete

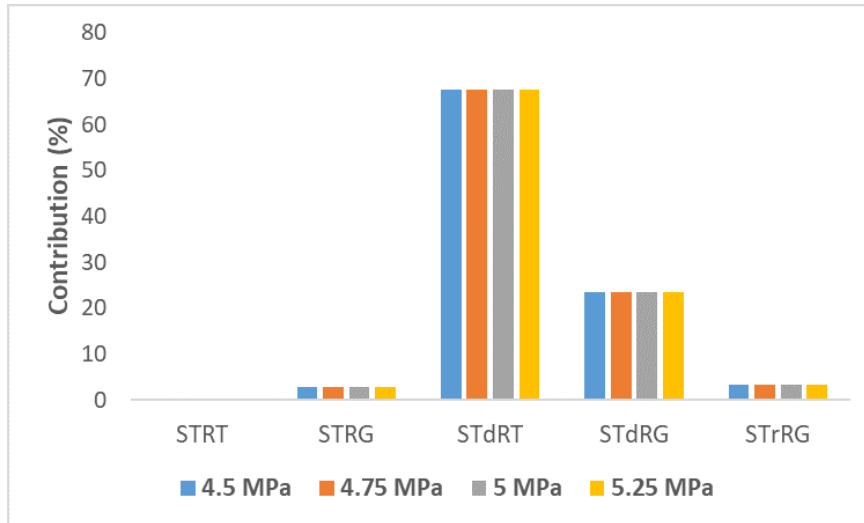
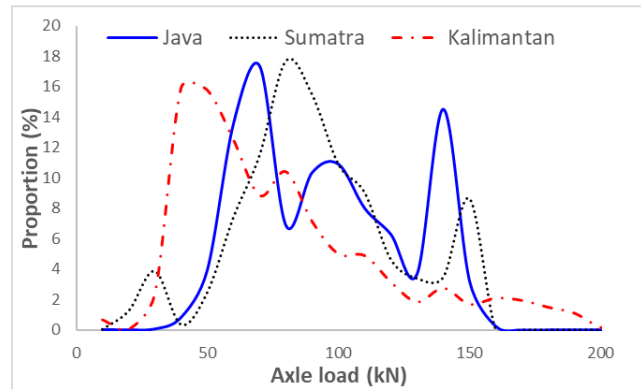


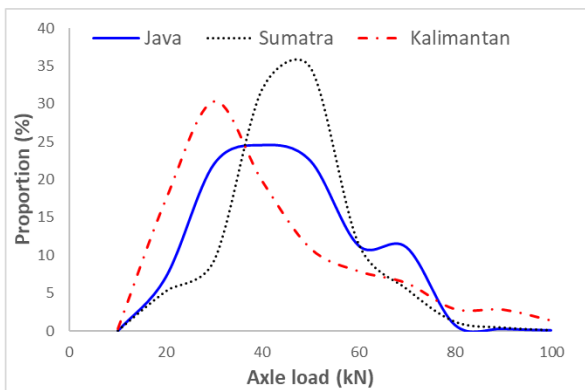
Figure 6. Percentage Contribution of Axle Load Types to Erosion Demand for Various Flexural Strengths of Concrete

4.3. Influence of Regional Axle Load Distribution

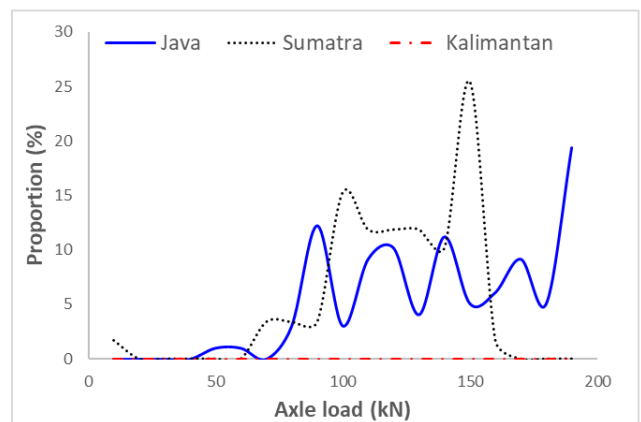
The impact of the axle load pattern is critical to the detectors, especially those with rigid pavements. Different areas exhibit different load spectra. This results in different changes in the pavement edges in different areas. In the long run, it influences the degree of stress in pavements, which affects the thickness and longevity of the service life. To demonstrate this effect, this study examined three regions in Indonesia: Java, Sumatra, and Kalimantan, which have varying traffic characteristics. From the MDPJ 2024, the axle load distributions are presented and illustrated in Figure 7 for different axle configurations (single, tandem, and triple axles; single and dual wheels). The distribution plots illustrate the varying proportions of axle loads in different regions for each configuration within the defined load range.



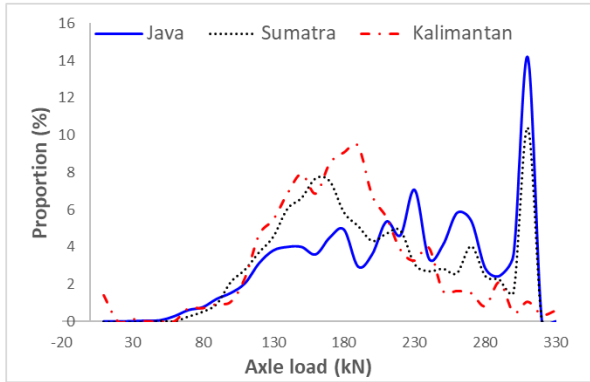
b. STRG



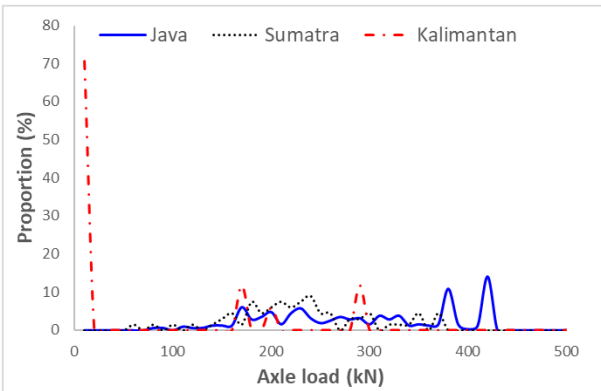
a. STRT



c. STdRT



d. STdRG



e. STRRG

Figure 7. Axle Load Distribution by Configuration Across Java, Sumatra, and Kalimantan

The differences in regional distribution were significant. The wider distribution of axle loads in Java for all configurations suggests that the region has more heterogeneous and heavier traffic. In contrast, Sumatra appears to have a more standardised loading, as reflected in concentrated peaks at particular intervals of axle loads.

Meanwhile, Kalimantan’s data suggest lighter loads due to fewer high-magnitude peaks and less overall traffic. These regional characteristics are likely to affect the pavement thickness and subsequent performance criteria, particularly erosion. This is because erosion is most affected by frequent medium- and heavy-axle loads. Using MDPJ 2024, this section explores the effects of differences in axle load spectra on pavement design outcomes within the same design framework.

Regional differences in the axle load distribution have also led to different design outcomes for the rigid pavement in terms of the slab thicknesses required for each region at different subgrade CBR levels, as shown in Figure 8. The results show that for Java, Sumatra, and Kalimantan, for all CBR levels, the same slab thicknesses are in descending order. This can be directly explained by the differences in the axle load spectra for each region, as shown in Figure 7.

For example, a subgrade CBR of 2% requires thicknesses of 410, 350, and 310 mm in Java, Sumatra, and Kalimantan, respectively. The subgrade strengths are also Java’s 10% CBR and a 320 mm slab versus Kalimantan’s 280 mm. This shows how traffic loading and axle configuration affect slab thickness. Java has a higher proportion of medium-to-heavy axle loads, which leads to more pavement stress and requires thicker slabs to meet fatigue and erosion criteria.

In contrast, Kalimantan features a more uniform and lighter axle load distribution, leading to lower stress concentrations at the edge of the pavements; therefore, thinner designs are required compared to Sumatra. This illustrates that, with the same subgrade strength, the axle load distribution affects the structural thickness. Hence, there is a need for a more precise pavement design per region, considering the actual traffic. This validates the MDPJ 2024, which states that pavement design must consider the subgrade strength while also considering the axle load present in a region for an optimised design with durability, efficiency, and economic balance.

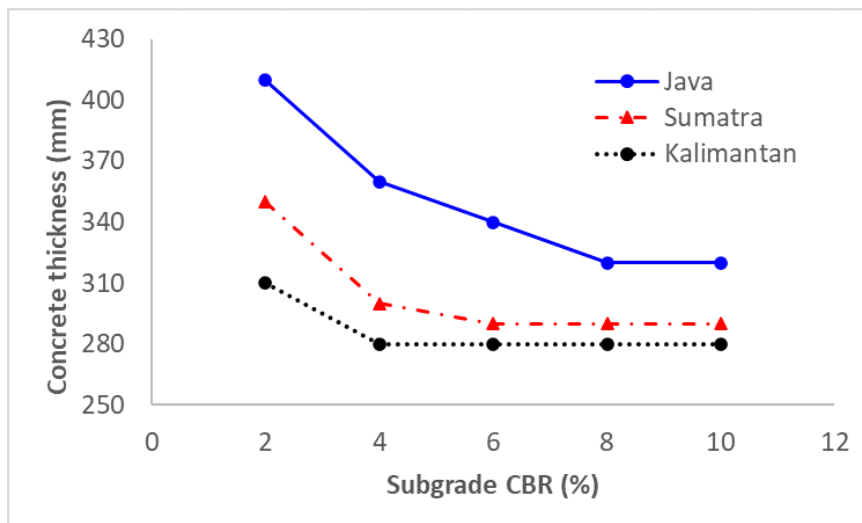


Figure 8. Concrete Pavement Thickness for Java, Sumatra, and Kalimantan under Varying Subgrade CBR Conditions

4.4. Practical Implications for Pavement Design Practice

This study provides several practical insights into the application of the MDPJ 2024 for rigid pavement design. The results demonstrate that the subgrade CBR and regional axle load distribution are the primary parameters governing the required concrete slab thickness, whereas variations in the concrete flexural strength have a negligible influence under erosion-controlled design scenarios. This indicates that for pavements subjected to moderate-to-heavy traffic, erosion rather than fatigue is the dominant performance criterion. From a mechanistic perspective, this behaviour reflects the sensitivity of the slab–subbase interaction to repeated axle loading at the slab edges, where pumping and loss of support can occur. Accordingly, designers should prioritise erosion control measures, including adequate subbase thickness and stiffness, enhanced subbase durability, effective edge support, and reliable drainage systems, rather than relying on higher concrete strength to reduce slab thickness.

The findings further suggest that the optimisation of rigid pavement design under MDPJ 2024 should focus on improving foundation performance rather than slab material strength alone. Increasing the concrete flexural strength beyond the minimum requirement does not reduce the slab thickness when erosion governs the design, as the critical response is controlled by the load transfer and subbase support conditions. Therefore, design optimisation efforts should be directed towards appropriate subbase selection, improved subgrade characterisation, and construction practices that minimise erosion susceptibility, such as ensuring adequate compaction and preventing moisture accumulation at the slab–subbase interface. This approach aligns with the intent of the mechanistic–empirical design principles embedded in the MDPJ 2024 and promotes a more rational allocation of material resources.

The regional analysis highlighted the critical role of the axle load distribution in determining the pavement thickness. Java, characterised by heavier and more heterogeneous axle load spectra, consistently requires thicker pavement sections than Sumatra and Kalimantan, regardless of the subgrade condition. This outcome demonstrates that pavement designs based solely on national average traffic assumptions may result in overdesign in regions with lighter traffic or underdesign in heavily trafficked corridors. Such misalignment affects structural performance and has implications for construction cost, maintenance planning, and long-term pavement sustainability. To achieve structurally efficient and context-sensitive designs, regional axle load distributions should be explicitly incorporated into the design process whenever feasible.

From a cost perspective, the erosion-governed nature of the design has significant implications. Increasing the concrete flexural strength beyond the minimum

requirement specified in MDPJ 2024 does not result in thinner slabs and, therefore, may not be cost-effective. Higher-strength concrete typically involves increased material and production costs without providing proportional structural advantages. Greater economic efficiency can be achieved by optimising the slab thickness through improved subgrade characterisation, appropriate subbase selection, and the use of realistic regional traffic data. These findings suggest that careful calibration of the design inputs offers more potential for cost optimisation than increasing the concrete strength alone.

Finally, the strong sensitivity of pavement thickness to regional axle load characteristics underscores the need for improved traffic data-collection practices. The implementation of weigh-in-motion systems, targeted axle load surveys on freight corridors, and the integration of traffic data from toll roads and industrial access routes would significantly enhance the reliability of the design inputs under the MDPJ 2024. Regular updates of regional axle load spectra would further support adaptive and evidence-based pavement designs. By combining accurate subgrade assessment, region-specific traffic data, and an erosion-focused design approach, engineers can deliver rigid pavement solutions that are structurally sound, economically efficient, and well-suited to Indonesia's diverse geographic and traffic conditions.

5. Conclusions

This study focused on subgrade strength, concrete flexural strength, and the distribution of axle loads in a region, using the Indonesian Road Pavement Design Manual (MDPJ) (2024) and its implications on rigid pavement design. The impact of modifications in the input variables on the pavement thickness and performance of the constructed pavement (fatigue and erosion) was assessed using a scenario design. A scenario design approach provides a way to assess various design scenarios.

The conclusions of this study indicate that the CBR of the subgrades and regional axle load distributions are the most decisive parameters for slab thickness determination. Significantly thicker slabs were required to accommodate lower CBR levels, and pavements in regions with more robust axle loads (Java) required stronger pavements than those in Sumatra and Kalimantan. Conversely, flexural concrete slabs of 4.5 MPa and 5.25 MPa, compared to proven slabs under the design conditions, governed erosion; hence, slab thickness reduction was not achieved because fatigue was the governing factor. It can be inferred from the findings that the advantages of the structure for erosion control in a concrete system are diminished. The study also analysed axle-type erosion contributions, where double axles and single wheels (STdRT) caused the most severe erosion impact, confirming their importance in erosion control design.

Responding to these concerns highlights the importance of customised pavement structures and the need to accurately measure traffic and axle loads for each area of study. Designing pavement structures without data is a waste of time and resources. While MDPJ 2024 provides sufficient latitude for design sensitivity, the accuracy of these designs depends on how well each design variable is calibrated.

Identifying the most applicable design guidelines for rigid pavement systems should assist road and transport infrastructure practitioners and planners in Indonesia. It is of utmost importance that geotechnical variables, axle loads, and erosion potential fulfill the design requirements in a synergistic manner to ensure that the economic and structural criteria of pavement systems are satisfactorily met.

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Author Contributions

RS prepared the manuscript, TD reviewed the manuscript, MK performed the analysis, and TA reviewed the manuscript.

Data Availability

Data analysis: <https://zenodo.org/records/15381370>

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