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# Evolution of Drainage Treatment in Flexible Pavement Design: Evolution of Drainage Treatment in Flexible Pavement Design: A Comparison of Three Generations of Design Methods

**Y. Djoko Setiyarto*, Mochamad Wildan Pratama Augustiawan**

Department of Civil Engineering, Faculty of Engineering and Computer Science, Universitas Komputer Indonesia, Unikom Smart Building, 11th Floor, Jl. Dipatiukur No. 102–116, Kota Bandung, Jawa Barat 40132, Indonesia

*Correspondence: y.djoko.setiyarto@email.unikom.ac.id

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**ABSTRACT:** Drainage played a crucial role in flexible pavement performance because moisture accumulation reduced material stiffness, accelerated fatigue cracking, and shortened service life. Along with the evolution of pavement design practice in Indonesia, the concept of drainage shifted from empirical correction toward a mechanistic–empirical system-based design approach. This study examined the evolution of drainage treatment in flexible pavement thickness design by comparing three generations of design methods: the 1993 American Association of State Highway and Transportation Officials (AASHTO) method, the 2017 Indonesian Pavement Design Manual, and the 2024 Indonesian Pavement Design Manual. Quantitative simulations were conducted for the first two methods under three drainage conditions (good, moderate, and poor) to evaluate the influence of drainage on pavement thickness. The 2024 manual was analyzed conceptually because it no longer applied numerical drainage correction but instead emphasized physical drainage system design. The results showed that deterioration of drainage quality from good to poor increased total pavement thickness by approximately 43.2% in the 1993 method and 43.75% in the 2017 manual. In contrast, the 2024 manual did not apply numerical thickness correction, as drainage effects were addressed through permeable layers and subsurface drainage systems. This study demonstrated a paradigm shift from empirical corrective design toward preventive mechanistic–empirical drainage design and discussed its relevance to international pavement engineering practice in moisture-sensitive and tropical environments.

**KEYWORDS:** Flexible pavement drainage; mechanistic–empirical design; pavement thickness; tropical climate; pavement design evolution

## 1. Introduction

Drainage played a fundamental role in sustaining the long-term performance of flexible pavements. Water that infiltrated or became trapped within pavement layers reduced the resilient modulus of the subgrade, accelerated fatigue cracking, and shortened pavement service life. The 1993 American Association of State Highway and Transportation Officials (AASHTO) design method, which formed the foundation for Indonesia's pavement design guidelines, incorporated the drainage coefficient (m) to adjust the contribution of granular layers to the Structural Number (SN) [1]. The same concept was formally adopted in the Indonesian Flexible Pavement Design Guideline No. 002/P/BM/2011, maintaining the empirical drainage correction approach. A methodological shift occurred with the introduction of the Pavement Design Manual (MDP) 2017, which supplemented empirical concepts with semi–mechanistic–empirical principles while retaining the drainage coefficient (m) [2]. This manual explicitly stated that inadequate subsurface drainage should be offset by increasing granular layer thickness, reflecting continued reliance on empirical corrections for moisture issues. The most substantial change was observed in MDP 2024, which eliminated numerical drainage coefficients and replaced them with a fully mechanistic–empirical framework emphasizing the physical design of drainage layers, subsurface drains, and infiltration control systems (Figures 1 and 2) [3].

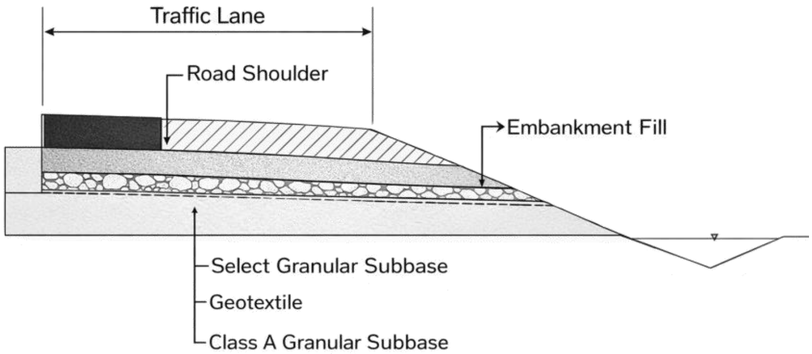


**Figure 1.** Embankment with Continuous Subbase Layer Extending to the Shoulder (MDP 2024).

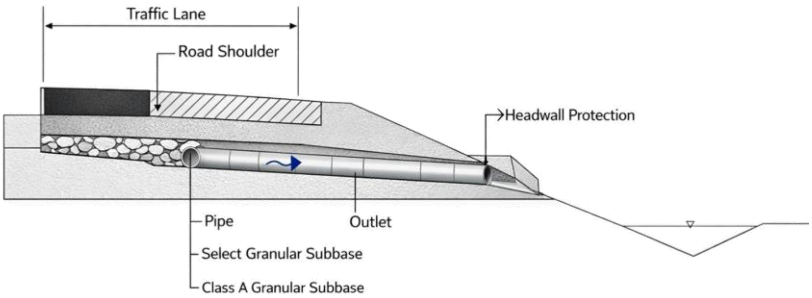


**Figure 2.** Shallow Drainage System with PVC Pipe Beneath Road Shoulder (MDP 2024).

Recent research has emphasized the importance of designing pavements that respond effectively to moisture, particularly under climate change scenarios characterized by higher temperatures, more intense rainfall, and frequent flooding [4]. Comparative analyses of AASHTO 1993 and MDP 2024 revealed that differences in pavement design primarily arose from how each method addressed drainage and moisture impacts [5]. Similar findings were observed in comparisons between AASHTO 1993 and MDP 2017, where pavement thicknesses varied due to modifications in traffic modeling, material modulus values, and drainage strategies [6]. Studies on drainage systems indicated that traditional empirical factors, such as the m coefficient, inadequately captured the complex interactions between water and pavement mechanics under fluctuating moisture conditions [7]. Research on sustainable pavement drainage systems confirmed that subgrade moisture control, subsurface drainage design, and drainage effectiveness were critical determinants of long-term pavement performance [8]. Long-term investigations demonstrated that well-designed subsurface drainage systems significantly improved asphalt pavement performance by reducing the duration of saturation in unbound layers [9]. Studies on pavement deterioration under climate change highlighted that performance depended on structural configuration, traffic loads, and environmental variability, factors that empirical models could not fully represent [10]. Mechanistic analyses further showed that empirical approaches failed to capture the complex response of pavement structures under variable moisture, especially in wet tropical regions [11].

Studies on climate change impacts reinforced the need for advanced drainage strategies because empirical drainage coefficients did not account for long-term hydrological dynamics [12]. Flood-vulnerability research recommended system-level subsurface drainage planning and moisture-sensitive design approaches, consistent with the conceptual shift observed in MDP 2024 [13]. Moisture-related structural damage studies confirmed that water-induced modulus reduction could not be adequately represented by empirical coefficients [14]. Data-driven analyses of flooded pavements demonstrated that moisture cycling dominated structural damage and distress propagation [15]. Material-specific studies indicated that the resilient modulus of granular layers was highly sensitive to water content variations, underscoring the limitations of empirical drainage parameters in traditional design frameworks [16]. Research on pavement resilience to flooding recommended integrated drainage systems and mechanistic seasonal corrections, as reflected in MDP 2024 [17]. Short-term post-flood pavement behavior studies also highlighted that residual saturation in subgrade and granular layers significantly weakened structural performance, a limitation not addressed by empirical drainage coefficients in AASHTO 1993 [18].

Despite extensive research on moisture-induced pavement damage and comparisons between AASHTO 1993 and MDP 2017, no studies have evaluated all three methods, including MDP 2024, in a high-rain tropical environment. This gap is particularly critical in Indonesia, where frequent heavy rainfall accelerates structural decay, and empirical drainage correction may no longer adequately represent long-term hydromechanical behavior. Understanding this evolution is important for national practice and contributes to the global discourse on the transition from empirical to mechanistic–empirical pavement design frameworks under climate-sensitive conditions. From a practical perspective, evaluating changes in drainage treatment is essential for extending pavement service life, reducing maintenance costs, and constructing resilient infrastructure in tropical regions experiencing increased rainfall variability. Therefore, this study aimed to: (1) compare drainage treatment concepts in the 1993 AASHTO method, the 2017 Indonesian Pavement Design Manual, and the 2024 Indonesian Pavement Design Manual; (2) quantify the influence of drainage conditions on pavement thickness using numerical simulations for the 1993 and 2017 methods; (3) evaluate the conceptual shift introduced in the 2024 manual toward system-based drainage design; and (4) demonstrate how this evolution reflects the transition from empirical to mechanistic–empirical drainage philosophy in moisture-sensitive tropical environments (Figures 1 and 2).

## 2. Materials and Methods

This study adopted a comparative–descriptive research design to examine the evolution of drainage concepts and their influence on flexible pavement thickness across three major pavement design frameworks: AASHTO 1993, MDP 2017, and MDP 2024. The analysis combined quantitative simulations and qualitative conceptual assessment. For the quantitative component, AASHTO 1993 and MDP 2017 were evaluated by modeling pavement thickness under varying drainage conditions, reflecting their reliance on the drainage coefficient (m) as a numerical modifier for granular layer performance. Qualitatively, the study reviewed the structural and conceptual shifts introduced in MDP 2024, which replaced numerical drainage correction with a fully mechanistic–empirical system emphasizing physical drainage components such as drainage layers, subsurface drains, and infiltration control elements [19, 20].

*2.1. Study area and field conditions.*

The study was conducted along Road Segment X in West Seram Regency, Maluku Province, an area characterized by heavy annual rainfall and large fluctuations in soil moisture content. These conditions highlighted the critical importance of effective drainage in preserving pavement integrity, as extended saturation accelerates subgrade weakening and structural deterioration [21]. Field observations identified multiple locations with inadequate drainage, including standing water on pavement surfaces and shoulders. These observations provided the empirical basis for the drainage–performance analysis, as illustrated in Figure 3, which depicts overall field conditions and confirms the presence of moisture-related distress along the study corridor.

**Figure 3.** Study location and field conditions illustrating moisture-related pavement distress.

*2.2. Design inputs and material characterization.*

Design inputs were obtained from traffic counts, subgrade testing, and material specifications. Traffic was expressed in cumulative ESALs of $0.11 \times 10^6$ at 80% reliability with a $\Delta PSI$ loss of 1.9. Laboratory tests indicated a subgrade CBR of 3.23%, typical of tropical soils with low stiffness under wet conditions [22]. Layer coefficients were derived from the design manuals: $a_1 = 0.39$ (HRS-WC asphalt wearing course), $a_2 = 0.14$ (LFA-A base), and $a_3 = 0.13$ (LFA-B subbase). These parameters were incorporated into pavement design simulations following established empirical and mechanistic–empirical modeling procedures [23].

*2.3. Drainage scenarios for AASHTO 1993 and MDP 2017.*

For AASHTO 1993 and MDP 2017, drainage was modeled using three m-value scenarios: m = 1.0 (good drainage), m = 0.7 (moderate drainage), and m = 0.4 (poor drainage), corresponding to realistic conditions reported in empirical studies and design guidelines. Reductions in m resulted in decreased structural contribution from granular layers, necessitating increased pavement thickness to offset moisture-induced strength loss. Pavement thickness was calculated for all three drainage scenarios according to the respective design rules, with all other input parameters held constant to isolate the effect of drainage on structural requirements.

*2.4. Conceptual analysis for MDP 2024.*

In contrast, drainage analysis for MDP 2024 was performed conceptually because the manual no longer included a drainage coefficient or numerical correction for moisture effects. Drainage was treated as an integral structural component, in line with mechanistic–empirical principles. Chapter 5 of MDP 2024 was reviewed to determine how drainage performance was ensured through the physical design of drainage layers, subsurface drains, and surface and shoulder slope management, rather than through numerical thickness adjustments [25]. This approach reflects a paradigm shift toward preventive moisture management within the pavement structure.

*2.5. Analytical and comparative procedure.*

The analytical procedure consisted of two stages. First, quantitative simulations were conducted for AASHTO 1993 and MDP 2017 to determine pavement thickness under each drainage scenario. Absolute thickness values, differences relative to the good drainage condition, and percentage increases were calculated to quantify the sensitivity of each design method to drainage degradation. These percentage changes served as effect-size indicators of drainage influence on pavement thickness. Second, a qualitative comparative assessment was performed to evaluate the conceptual transformation in MDP 2024, focusing on the transition from numerical moisture correction to system-based drainage design. The results were compared side-by-side to highlight thickness differences between AASHTO 1993 and MDP 2017, and to illustrate the conceptual advancements in MDP 2024. This approach provided a comprehensive view of the evolution in Indonesian pavement design, demonstrating the shift from empirical drainage corrections to mechanistic–empirical strategies that enhance resilience under moisture-sensitive tropical conditions.

## 3. Results and Discussion

The findings of this study demonstrated that differences in drainage treatment and calculation approaches across the three design methods significantly influenced the resulting flexible pavement thickness. AASHTO 1993 relied entirely on an empirical framework, in which drainage performance was expressed numerically through the drainage coefficient (m). MDP 2017 represented a transitional stage, incorporating semi mechanistic–empirical concepts while still depending on (m) for moisture correction based on design charts. In contrast, MDP 2024 abandoned numerical drainage correction altogether and replaced it with a structural, system-based drainage design approach that integrated subsurface drainage, permeable layers, and infiltration control as part of the pavement structure. This shift had meaningful implications for the prediction and control of pavement performance, particularly in moisture-sensitive tropical environments.

### *3.1. Influence of drainage coefficient on pavement thickness.*

Simulations using AASHTO 1993 clearly illustrated the relationship between reduced drainage quality and increased pavement thickness. Under good drainage conditions (m = 1.0), the total pavement thickness was approximately 350 mm. As drainage performance decreased to moderate (m = 0.7), total thickness increased to 490 mm. Under poor drainage (m = 0.4), the thickness rose to approximately 810 mm, representing an increase of roughly 43.2% relative to good drainage conditions. This increase reflected the reduced contribution of granular layers to the Structural Number (SN) as their stiffness declined under prolonged moisture exposure. In this empirical framework, lower values of (m) represented longer saturation periods, requiring additional thickness to maintain equivalent structural capacity.

A similar pattern was observed in MDP 2017, although the applicable range of drainage coefficients was narrower, as defined in the design charts of the manual. Under good drainage (m = 1.0), the total thickness was approximately 350 mm. When drainage quality decreased to moderate (m = 0.7), total thickness increased to 480 mm. Under poor drainage (m = 0.4), the required thickness reached approximately 800 mm, representing a 43.75% increase relative to the good drainage scenario. These results indicated that although MDP 2017 incorporated semi mechanistic–empirical concepts, such as layer modulus and strain-based performance indicators, the impact of drainage remained governed by empirical correction, maintaining a strong sensitivity to drainage performance. The calculated thicknesses for aggregate base layers under different drainage conditions are summarized in Table 1, and the resulting pavement configurations for m = 1.0 and m = 0.7 are shown in Figure 4 and Figure 5, illustrating the increase in base thickness under reduced drainage performance. The absolute and percentage increases relative to the good drainage condition were used as effect-size indicators to quantify the sensitivity of each method to drainage degradation.

**Table 1.** Summary of aggregate base thickness according to AASHTO 1993 and MDP 2017.

| **Method** | **m = 1** | | **m = 0.7** | | **m = 0.4** | |
|---|---|---|---|---|---|---|
| | Class A (mm) | Class B (mm) | Class A (mm) | Class B (mm) | Class A (mm) | Class B (mm) |
| AASHTO 1993 | 150 | 150 | 220 | 220 | 380 | 380 |
| MDP 2017 | 150 | 150 | 215 | 215 | 375 | 375 |

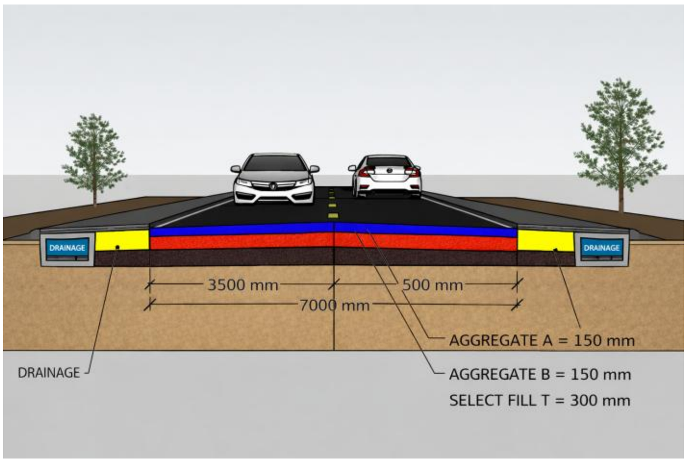


**Figure 4.** Pavement thickness under good drainage condition (m = 1.0).

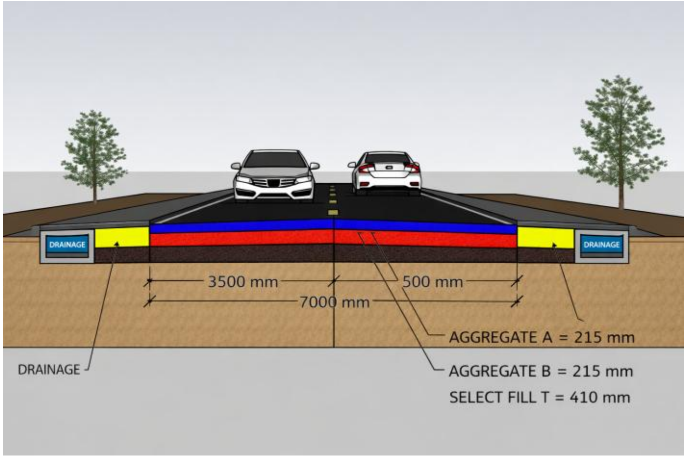


**Figure 5.** Pavement thickness increase under moderate drainage condition (m = 0.7).

### *3.2. Conceptual drainage approach in MDP 2024.*

Unlike the previous two methods, MDP 2024 no longer included numerical drainage correction. Instead, Chapter 5 of MDP 2024 presented drainage as a structural system designed to prevent moisture accumulation in pavement layers. This represented a fundamental shift from "moisture correction through thickness increase" to "moisture prevention through physical design." MDP 2024 emphasized subsurface drainage layers, subdrains, and careful control of surface and shoulder slopes to facilitate rapid water removal. As a result, moisture-induced stiffness reduction was prevented at the source rather than compensated through increased structural thickness. This approach aligned with mechanistic–empirical principles, in which structural response, moisture conditions, and actual pavement behavior governed design decisions. The structural concept adopted by MDP 2024 is illustrated in Figure 6 and Figure 7. Figure 6 shows a drainage layer configuration in which the subbase (Class B material) extends continuously below the shoulder toward the roadside drain, ensuring rapid water discharge. Figure 7 depicts a subsurface drainage solution using a PVC pipe connecting the aggregate foundation layer directly to the drainage channel, preventing moisture buildup beneath the pavement.

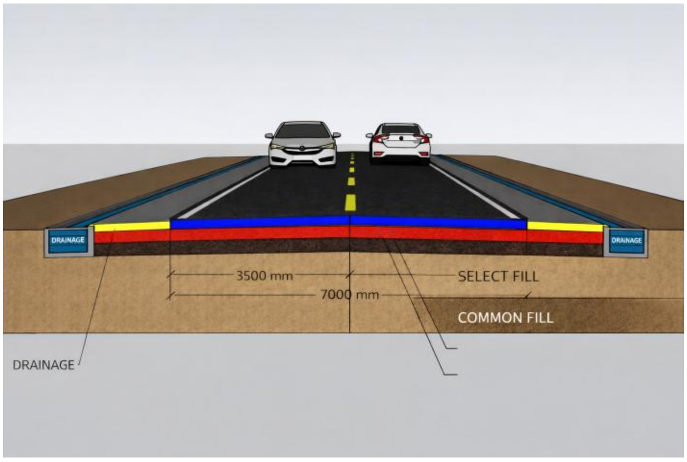


**Figure 6.** Pavement structure with extended Class B subbase toward drainage channel.

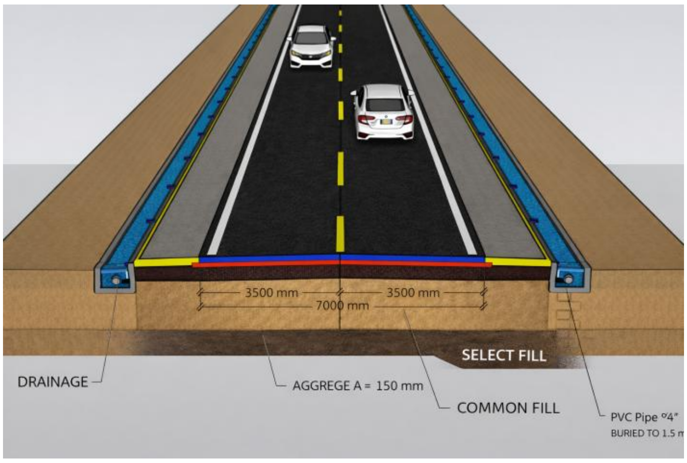


**Figure 7.** Pavement structure incorporating PVC pipe subsurface drainage.

### *3.3. Cross-method comparison and paradigm shift.*

A comparison of the three design methods revealed a clear progression from empirical to mechanistic–empirical drainage treatment. AASHTO 1993 treated drainage as a direct correction factor applied to layer contributions. MDP 2017 expanded this perspective by integrating material modulus and strain relationships, while still employing empirical drainage coefficients. MDP 2024 replaced these concepts with a fully preventive, system-based drainage design, marking a transition from reactive to proactive moisture management. This progression is summarized in Table 2, which highlights differences in approach, parameters, design focus, and underlying philosophy.

**Table 2.** Paradigm shift in flexible pavement design due to drainage considerations.

| Aspect | AASHTO 1993 | MDP 2017 | MDP 2024 |
|---|---|---|---|
| Approach | Empirical | Semi mechanistic–empirical | Mechanistic–empirical |
| Drainage Parameter | m (0.4–1.4) | m (0.4–1.0) | None |
| Focus | Correcting granular layer contribution | Correcting layer contribution and strain | Preventing moisture accumulation |
| Effect on Design | Poor drainage → thicker pavement | Poor drainage → thicker pavement | Requires drainage layers |
| Philosophy | Corrective | Transitional | Preventive |

The results confirmed that drainage was no longer treated as a single empirical parameter but as an essential structural component of pavement design. MDP 2024 reflected a mature mechanistic–empirical perspective in which moisture was controlled through engineering design rather than numerical adjustment. This shift was particularly crucial for Indonesia's tropical climate, where high rainfall and frequent saturation events constituted major contributors to pavement deformation and early failure. Whereas empirical methods translated drainage deficiencies into increased layer thickness, MDP 2024 required designers to ensure that water did not remain an uncontrolled variable within the pavement system. The progression from AASHTO 1993 to MDP 2024 represents not merely a change of design equations, but a fundamental evolution in roadway engineering philosophy—from empirical moisture correction toward mechanistic control of pavement structural performance. This paradigm shift makes Indonesia's pavement design methodology more resilient, scientifically grounded, and better suited for climate-sensitive environments.

### *3.4. Limitations of empirical drainage coefficients and implications for mechanistic–empirical design.*

The results confirmed that both AASHTO 1993 and MDP 2017 remained highly sensitive to variations in drainage quality because drainage performance was represented solely by an empirical coefficient (m). The observed increase in pavement thickness exceeding 40% under poor drainage conditions indicated that moisture effects were translated into structural demand only through numerical correction, rather than through direct control of moisture within the pavement system. This finding was consistent with international studies showing that empirical drainage coefficients could not adequately capture long-term hydromechanical pavement behavior under variable moisture conditions, especially under repeated wetting–drying cycles and prolonged saturation [7, 8, 14].

In tropical and high-rainfall environments such as Indonesia, the limitations of this empirical approach became more pronounced. High rainfall intensity, frequent ponding, and slow subsurface drainage led to prolonged moisture retention in unbound layers, causing significant reductions in resilient modulus and accelerated structural deterioration. Previous studies showed that moisture-induced damage and stiffness degradation could not be reliably represented by a single empirical factor, because pavement response was governed by complex interactions between material properties, drainage conditions, traffic loading, and climate variability [10, 15, 16]. Therefore, relying solely on the drainage coefficient (m) could result in designs that compensated for moisture problems by increasing thickness, rather than addressing the root cause of moisture accumulation.

The shift toward system-based drainage design in MDP 2024 aligned with global mechanistic–empirical trends that emphasized moisture control through structural configuration rather than numerical correction factors [9, 17]. By integrating drainage layers, subsurface drains, and geometric controls into the pavement structure, the new approach sought to prevent moisture from remaining in the system, instead of correcting its effects after the fact. Similar approaches had been recommended in international mechanistic–empirical frameworks, which highlighted that pavement performance prediction should be based on structural response and environmental loading rather than empirical adjustment alone [11, 20].

From a design philosophy perspective, this transition represented a move from reactive to preventive moisture management. Empirical methods such as AASHTO 1993 and, to a lesser extent, MDP 2017, treated drainage as an external modifier of layer contribution, whereas MDP 2024 treated drainage as an integral structural component of the pavement system. This conceptual evolution was particularly relevant for climate-sensitive regions, where increasing rainfall variability and extreme weather events further reduced the reliability of purely empirical correction factors [4, 12]. Consequently, the adoption of a mechanistic–empirical, system-based drainage approach provided a more physically realistic and resilient framework for flexible pavement design in tropical environments.

## 4. Conclusions

This study demonstrated that drainage plays a fundamental role in determining flexible pavement performance and structural thickness, and that its treatment varied substantially across AASHTO 1993, MDP 2017, and MDP 2024. The results showed that both AASHTO 1993 and MDP 2017 responded to poor drainage conditions by increasing pavement thickness through numerical adjustments using the drainage coefficient (m). Under deteriorating drainage—from m = 1.0 to m = 0.4—the structural thickness increased by more than 40%, clearly highlighting the sensitivity of empirical and semi mechanistic–empirical methods to moisture conditions. In contrast, MDP 2024 introduced a paradigm shift by eliminating numerical drainage corrections and adopting a mechanistic–empirical drainage system that emphasized moisture prevention through physical design measures, including drainage layers, subsurface drains, and infiltration control. This approach reflected a transition from reactive, empirically driven moisture adjustments to proactive structural design that stabilized moisture conditions from the outset. The comparison confirmed that MDP 2024 provided a more realistic and resilient methodology for tropical environments characterized by high rainfall and moisture variability. Therefore, the evolution from AASHTO 1993 to MDP 2024 represented not merely an update in calculation methods, but a fundamental reframing of drainage as an integrated structural system rather than a numerical modifier. This study was subject to several limitations. The numerical comparison was based on deterministic simulations and did not include a full probabilistic uncertainty analysis. The evaluation of the 2024 manual was conceptual and not yet supported by long-term field performance data. In addition, the case study represented a tropical, high-rainfall environment and may not fully represent other climatic regions. Future research should include field validation of system-based drainage designs, climate-change-oriented performance modeling, and application of the proposed framework to other tropical and subtropical regions.

## Author Contributions

Y. Djoko Setiyarto led the study conceptualization, methodological design, supervision, and manuscript revision. Mochamad Wildan Pratama Augustiawan conducted data collection, field investigations, numerical simulations, and prepared the initial manuscript draft. Both authors contributed to data interpretation and approved the final manuscript.

## Data Availability Statement

All data supporting the findings of this study, including traffic data, subgrade CBR measurements, design parameters, and simulation outputs, are available from the authors upon reasonable request. Field documentation and supplementary design calculations used in the analysis may also be accessed by contacting the corresponding author. No proprietary or confidential data were used in this research.

## Competing Interest

The authors declare that there are no competing financial, professional, or personal interests that could have influenced the work reported in this manuscript. The research was conducted independently and without any external interference.

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