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Sustainability Assessment of Expansion Joint Systems: Comparative Analysis of Asphaltic Plug and Strip Seal Joints on Indonesian Highway Bridges

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Abstract

Bridge expansion joints play a vital role in accommodating structural movements and sustaining traffic loads, yet their performance outcomes vary significantly across joint systems. This study conducts a comparative analysis of Asphaltic Plug Joints (APJ) and Strip Seal Joints (SSJ) on the Krian–Mojokerto Highway Bridge, East Java, Indonesia. The research combines direct field observations of installation and operational performance with secondary data from national standards and cost records of recent maintenance projects. Comparative parameters include installation stages and duration, initial construction cost, five-year life-cycle maintenance cost, durability, and safety performance. Findings show that APJ offers advantages in shorter installation time (7 hours versus 15 hours for SSJ) and lower initial cost (Rp. 2.17 million/m versus Rp. 11.45 million/m). However, APJ requires more frequent maintenance (every ±18 months), resulting in higher five-year costs (Rp. 109 million) and greater safety risks due to cracks and potholes. Conversely, SSJ demonstrates longer service intervals (up to four years), lower long-term costs (Rp. 36.9 million), and better safety outcomes, making it more sustainable for high-traffic bridges. The novelty of this research lies in presenting the first systematic comparison of APJ and SSJ under tropical, high-traffic conditions, integrating technical, economic, and environmental perspectives. The study recommends prioritizing SSJ for future infrastructure planning to enhance safety, durability, and sustainability in bridge expansion systems.

***Keywords**: Asphaltic Plug Joint, Bridge Maintenance, Life-Cycle Cost Analysis, Strip Seal Joint, Structural Durability*

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INTRODUCTION

Bridges are one of the most vital infrastructures, serving not only as connectors between regions but also as primary supports for economic and social mobility. In bridge construction, one component that often does not receive sufficient attention is the expansion joint system (Deng et al., 2023; Sha et al., 2022). Expansion joints play an important role in accommodating movements caused by temperature changes, traffic loads, and structural deformations (Huang et al., 2024; Javanmardi et al., 2022). If these joints do not function properly, damage to the bridge deck, disruption of driver comfort, and even potential traffic accidents may occur. Field evidence shows that expansion joint failure often becomes the starting point of greater structural damage, leading to far higher maintenance costs compared to if such problems had been anticipated from the outset (Miari et al., 2021; Y.-M. Zhang et al., 2021).

In the Indonesian context, which has a tropical climate with high temperatures and extreme humidity, bridge joint systems face different challenges compared to those in subtropical countries. Heavy traffic conditions, particularly on toll roads with high volumes of heavy vehicles, further complicate the problem (Barasa et al., 2023; Dharmayanti et al., 2023). A concrete example is the Krian–Mojokerto Toll Road in East Java, which serves as a vital route for logistics distribution and daily community mobility (Ongkowijoyo et al., 2020). On this route, bridge joints constitute vulnerable points requiring special attention from both technical and economic perspectives. Two types of joint systems commonly used are the Asphaltic Plug Joint (APJ) and the Strip Seal Joint (SSJ), each with its own advantages and disadvantages. However, the choice of joint type is often based on short-term considerations such as initial costs and installation speed, without adequately accounting for long-term performance, safety aspects, or environmental impacts resulting from frequent repairs.

Several previous studies have highlighted the importance of selecting the appropriate bridge joint system. For instance, Hidayat et al. (2022) and Riyanti et al. (2022) emphasized that expansion joints are the most critical points in bridge maintenance due to their direct exposure to traffic loads. Erythrina et al. (2021) showed that APJ systems often fail more quickly in tropical climates due to cracking and asphalt aggregate loss, especially when material quality and installation methods do not meet standards. Meanwhile, research by Kim et al. (2023) in Vietnam found that SSJs demonstrate higher durability under heavy traffic, although they require significantly higher initial costs. Studies by D. Kumar et al. (2024) and Park et al. (2022) in South Korea even confirmed that the high initial cost of SSJs can be offset in the long term due to longer repair intervals compared to APJs.

Furthermore, studies by Butt et al. (2022) and Shams et al. (2025) comparing bridge joint performance in Pakistan revealed that APJ failures are often caused by extreme temperature variations and heavy traffic, leading to early cracking of the asphalt surface. On the other hand, SSJs were found to be more stable under the same conditions. Similarly, research by Naeem et al. (2025) and H. Zhang et al. (2024) in Malaysia showed that although APJs are easier to install, their high repair frequency generates additional social and environmental costs due to congestion and pollution from repeated construction works. Uddin et al. (2023) further emphasized that joint type selection must consider traffic safety, since joint failures can directly endanger road users.

In the field of cost analysis, Life-Cycle Cost Analysis (LCCA) has been widely used to evaluate the effectiveness of joint systems. For example, Altaf et al. (2023) and Hamim et al. (2021) applied this method to assess road infrastructure performance in Bangladesh and found that while initial costs can be reduced, long-term maintenance costs largely determine system sustainability. Meanwhile, Nugroho et al. (2022) and Sastrawiria et al. (2024) in Indonesia stressed the importance of including tropical climate variables in the analysis, as these conditions affect the service life of bridge joints. Studies by Alaloul et al. (2021a, 2021b) in the Middle East also confirmed the same point, namely that environmental factors significantly accelerate the degradation of asphalt-based joints.

Other research by Wang et al. (2023) and Zini et al. (2024) in Japan showed that repair frequency of joints is strongly correlated with traffic disruptions and socio-economic costs. In other words, durable joint systems are not only technically advantageous but also provide broader benefits to society. Studies by Tumpa & Naeni (2025) and Wijaya (2022) in Indonesia further indicated that sustainability aspects are often overlooked in technical decision-making, whereas sustainable infrastructure should encompass cost efficiency, safety, and minimal environmental impact. Along the same lines, Hemmati et al. (2024) argued that the success of joint systems cannot be measured solely through technical parameters but must also be integrated with economic and social aspects.

Although the existing literature has extensively discussed the advantages and disadvantages of each joint system, most research still focuses on subtropical or temperate conditions and thus does not fully represent the challenges faced in tropical climates with dense traffic such as in Indonesia. Even within national-level studies, the discussion tends to emphasize installation techniques or initial costs, without providing a comprehensive overview of life-cycle costs, safety impacts, and environmental consequences. This highlights the importance of conducting a more comprehensive study, particularly with a direct comparative approach between APJ and SSJ within the context of high-traffic toll roads.

Therefore, this study seeks to fill that gap by providing a comparative analysis that integrates technical, economic, environmental, and safety aspects within a single evaluation framework. Through a case study of the Krian–Mojokerto Toll Road Bridge, this research not only presents a comparison of initial costs and installation times but also examines long-term maintenance costs and the social impacts of traffic disruptions. The approach adopted offers a new perspective on how to select joint systems that are not only cost-efficient but also safer, more sustainable, and environmentally friendly.

The main objective of this study is to provide a more robust foundation for policymakers and civil engineering practitioners in determining the most appropriate bridge joint type in Indonesia. By positioning APJ and SSJ within a life-cycle analysis framework, this research aims to generate relevant recommendations for more sustainable infrastructure development while simultaneously enriching the body of knowledge in the fields of civil and environmental engineering.

RESEARCH METHOD

This research is designed as a case study focusing on the Krian–Mojokerto Toll Road Bridge in East Java, Indonesia. The selection of this location is not without reason. The bridge is situated on one of the toll road sections with high traffic intensity, dominated by heavy vehicles, and located in a humid tropical climate. These conditions pose unique challenges for the performance of expansion joints, both in terms of material durability and maintenance frequency. With such characteristics, the research site is representative of the real problems faced by bridge joint systems in Indonesia, making the findings expected to be relevant not only academically but also practically for infrastructure policymakers.

Data collection was carried out through two main approaches, namely field observation and secondary data collection. Field observation was conducted to directly observe how Asphaltic Plug Joint (APJ) and Strip Seal Joint (SSJ) systems are installed and function under real traffic conditions. This observation included installation stages, execution time per lane, and the physical performance of the joints after a certain period. Direct observation was chosen because it provides factual insights that are not always captured in technical documents, such as field constraints, work quality, and the joints' responses to daily traffic loads. As emphasized by Fredricks (2022), field observation enables researchers to capture dynamics that cannot be explained solely by quantitative data.

Secondary data were collected from various official sources, including government standards such as the Circular of the Ministry of Public Works and Public Housing No. 11/SE/M/2015 and the 2018 Unit Price Analysis (AHS) documents, which provide technical and cost references for bridge joint works. In addition, up-to-date maintenance cost data from 2023 projects were used to calculate life-cycle costs over a five-year period. The use of secondary data is important as it allows the analysis to be conducted based on valid regulations and cost information, while minimizing subjective bias in data collection.

Data validation was carried out using triangulation, namely by comparing field observation results with secondary data as well as informal interviews with technical personnel involved in maintenance processes. Triangulation was chosen as it enhances the credibility of the research findings by combining multiple sources of information. For instance, discrepancies between official cost records and technical field experience can provide a more comprehensive understanding of the factors influencing joint performance.

The collected data were then analyzed using a comparative descriptive approach combined with Life-Cycle Cost Analysis (LCCA). Comparative descriptive analysis was used to directly compare differences in technical, economic, and safety aspects between APJ and SSJ. Meanwhile, LCCA was applied to calculate the total costs incurred over five years, including initial installation costs and routine maintenance expenses. LCCA was chosen because it provides a comprehensive overview of the long-term efficiency of a system, not merely based on initial costs (Azadgoleh et al., 2024; Renne et al., 2022). By combining these two methods, the study can deliver balanced results that account for both short-term and long-term considerations.

RESULTS AND DISCUSSION

Technical Characteristics of Joint Installation

Bridge expansion joints are critical components designed to accommodate structural movements caused by temperature changes, traffic loads, and dynamic vibrations. In modern bridge construction practice, the selection of joint type is not only based on initial costs but also on technical effectiveness, installation speed, and long-term durability. This study focuses on two types of closed expansion joints widely used in Indonesia, namely Asphaltic

Plug Joint (APJ) and Strip Seal Joint (SSJ). These two types were chosen because they are practically applied in the Krian–Mojokerto Toll Road Bridge, yet exhibit significant differences in terms of installation stages and technical performance.

Field observations revealed that APJ installation is relatively simple. The process begins with excavation or cutting of the designated joint gap. A steel plate and anchors are then installed to hold the filler material, followed by heating aggregates together with a binder at a specified temperature until homogeneous. The mixture is then poured into the joint gap. After cooling and hardening, the surface can be immediately opened to traffic. The total time required for APJ installation per lane is approximately 7 hours, making it a frequent choice for emergency works or maintenance requiring rapid reopening to traffic.

In contrast, SSJ installation is more complex and requires a longer sequence of steps. The process begins with preparation of the concrete surface, installation of the steel edge beam and anchors, and re-casting concrete around the beam. After the concrete has hardened, the elastomer strip is inserted and locked into the steel profile. This process requires high precision because installation errors can reduce joint performance in accommodating movement. Installation time per lane averages 15 hours, more than twice that of APJ. However, the end result produces a more stable joint with greater durability against heavy traffic and temperature fluctuations. The differences in technical installation characteristics of the two joints can be summarized in the following table:

Table 1 Comparison of Installation Stages and Time for APJ and SSJ

Technical Aspect	Asphaltic Plug Joint (APJ)	Strip Seal Joint (SSJ)
Installation stages	Excavation of gap, installation of steel plate & anchors, heating of asphalt + aggregate mix, pouring, cooling	Concrete preparation, installation of steel edge beam & anchors, re-casting concrete, installation of elastomer strip
Complexity level	Low–medium	High
Installation precision	Relatively simple	Very high (requires precision)
Time per lane	± 7 hours	± 15 hours
Readiness for traffic	Quick (after cooling)	Longer (requires concrete setting time)

Source: Field observation, 2023

The comparison shows that APJ has advantages in installation speed and technical simplicity. This condition provides benefits in emergency situations, such as rapid repair works on toll roads with heavy traffic. However, this simplicity has consequences for long-term durability, since joint quality is highly dependent on mixture homogeneity and compaction process. Even minor errors at this stage can result in early damage such as cracking or asphalt particle loss.

On the other hand, although SSJ requires longer installation time, it offers better long-term reliability. The precision in installing steel beams and elastomer strips allows the joint to withstand repeated deformation from heavy traffic loads. This technical complexity makes SSJ more suitable for bridges with high traffic volume, such as the Krian–Mojokerto section. This is consistent with Bulbaai & Halman (2021), who emphasized that efficiency in tropical infrastructure construction should not only be measured by installation speed but also by structural quality, which determines service life. The visual differences between these two joint types are also apparent. APJ essentially appears as an asphalt layer integrated with the road surface, while SSJ consists of a steel profile holding the elastomer strip. This difference directly affects performance. APJ appears smoother for road users but is vulnerable to cracking due to expansion–contraction cycles. Meanwhile, SSJ looks stiffer and more profiled, but structurally it is stronger in resisting both horizontal and vertical forces.

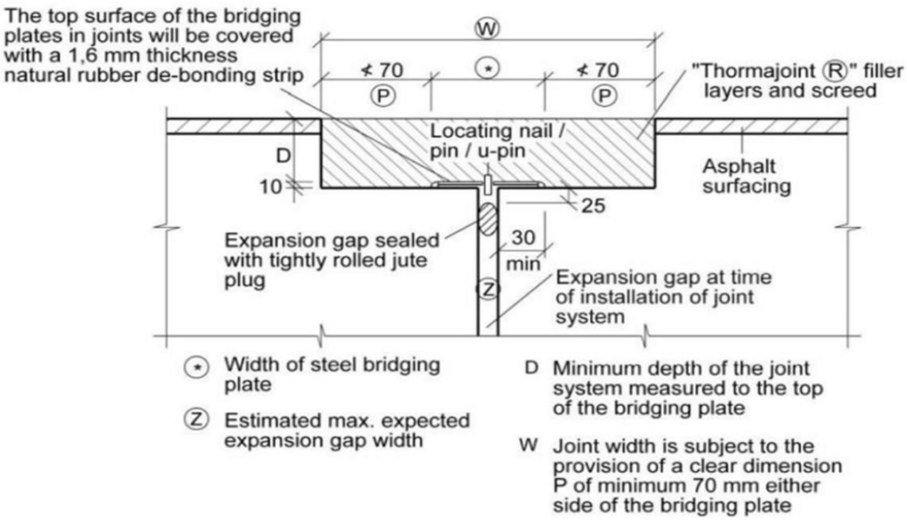

Figure 1 Asphaltic Plug Joint (APJ) on bridge deck surface
Source: Field documentation, 2023

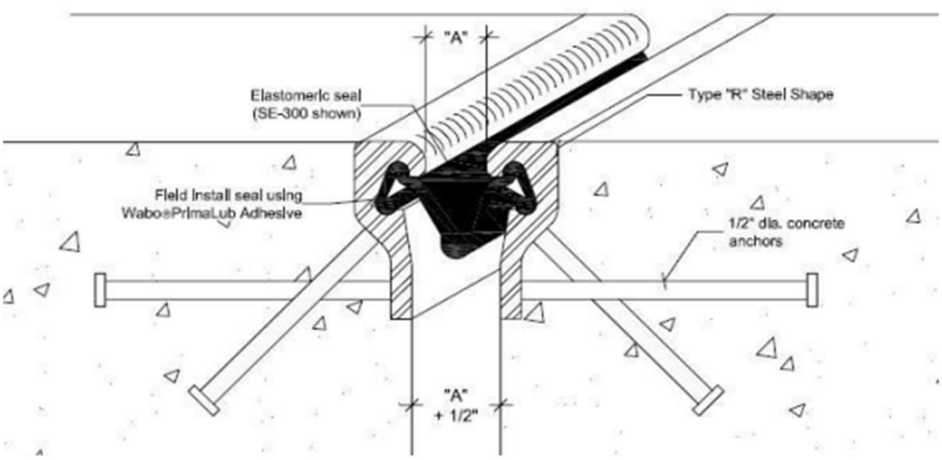

Figure 2 Strip Seal Joint (SSJ) with steel edge beam and elastomer strip
Source: Field documentation, 2023

In the context of Indonesia's tropical climate, these technical characteristics are even more important to consider. High daytime temperatures followed by significant nighttime drops accelerate degradation of asphalt-based materials such as APJ. Moreover, high rainfall increases the risk of damage due to water infiltration into cracks. These conditions make SSJ more adaptive to tropical environments, despite its longer installation time.

Initial Cost and Life-Cycle Cost Analysis

One of the most crucial aspects in evaluating the performance of bridge expansion joint systems is cost, both in terms of initial cost and life-cycle cost. The decision to select a joint type is not determined solely by installation price per meter, but also by the accumulated maintenance costs required over the bridge's service life. In the context of public infrastructure with heavy traffic such as the Krian–Mojokerto Bridge, cost considerations become increasingly strategic as they relate to sustainable budget allocation, road user safety, and service efficiency. Based on the analysis, APJ offers significantly lower initial costs compared to SSJ. APJ installation per meter requires only Rp. 2.17 million, while SSJ costs up to Rp. 11.45 million per meter. This substantial cost difference is often the main reason contractors or bridge managers choose APJ, particularly in projects with limited budgets. At first glance, APJ appears more economical as it reduces the upfront financial burden for government or related agencies.

However, the cost perspective does not end at the installation stage. When examined more deeply using a Life-Cycle Cost Analysis (LCCA), the differences in maintenance patterns between APJ and SSJ lead to highly contrasting implications. Over a five-year period, APJ requires maintenance on average every ±18 months, due to recurring damage such as cracks, potholes, or settlement at the joint. The accumulated maintenance costs over five years reach Rp. 109.01 million. By contrast, SSJ requires maintenance only every ±4 years, with relatively simple interventions such as replacing the rubber seal or filling cracks with epoxy. Its cumulative five-year maintenance cost is only about Rp. 36.93 million.

This comparison confirms that although APJ is cheaper at the initial stage, its long-term costs are actually higher. Meanwhile, SSJ, although more expensive at the outset, proves more economical in medium- to long-term maintenance cycles. These findings align with Lee et al. (2021) and Pragati et al. (2023), who argued that infrastructure cost evaluation should prioritize long-term orientation rather than short-term savings. They emphasized that sustainable projects must consider life-cycle performance, since repeated maintenance and traffic disruptions generate far greater losses if decisions are made solely on initial cost. The following table presents the cost comparison between APJ and SSJ.

The table 2 clearly shows that the cost paradigm between APJ and SSJ is highly contrasting. Although APJ requires lower initial investment, its five-year total cost exceeds Rp. 111 million, nearly three times higher than SSJ. This not only has implications for technical and financial aspects but also for social and environmental dimensions. The higher frequency of APJ maintenance potentially causes more frequent traffic disruptions, increases accident risk during repair periods, and generates a larger carbon footprint from repeated construction activities.

Table 2 Comparison of Initial and Life-Cycle Costs of APJ and SSJ (5 years)

Joint Type	Initial Cost per m (Rp)	Maintenance Interval	5-Year Maintenance Cost (Rp)	Total 5-Year Cost (Rp)
Asphaltic Plug Joint (APJ)	2,170,500	± 18 months	109,010,100	111,180,600
Strip Seal Joint (SSJ)	11,450,000	± 4 years	36,930,500	48,380,500

Source: Maintenance cost calculation for Krian–Mojokerto Bridge, 2023.

The LCCA approach is increasingly important in the context of sustainable development, where long-term efficiency and environmental sustainability are the main objectives. Pragati et al. (2023) emphasized that applying LCCA not only helps governments and contractors choose more durable materials or systems but also supports efficient allocation of public resources. In the Krian–Mojokerto case, if decisions were made solely on initial cost, APJ would always be selected. However, with the LCCA approach, SSJ proves far superior in terms of total costs as well as infrastructure sustainability implications.

Moreover, this comparison highlights the need for a paradigm shift in infrastructure planning. Many projects remain focused on saving installation costs, even though such approaches often result in hidden costs in the form of frequent maintenance, safety risks, and social losses from traffic disruptions. With SSJ, maintenance demands are lighter, road user safety is better preserved, and budget efficiency is higher in the long term.

From a socio-economic perspective, SSJ's long-term efficiency also reduces external costs borne by society. Less frequent maintenance decreases the likelihood of traffic congestion that can cause economic losses from delayed goods distribution and daily commuting. Thus, this analysis demonstrates that higher upfront investment in SSJ actually represents a strategy for mitigating future social costs.

Durability and Safety Performance

Field findings on the bridge segment along Krian–Mojokerto Regency Border Road show a significant difference between the performance of Asphaltic Plug Joint (APJ) and Strip Seal Joint (SSJ) in terms of durability and road user safety. In general, APJ expansion joints proved to be more prone to early damage. After an operational period of around 18 months, this type of joint began to exhibit cracking, potholes, and partial loss of steel plates due to heavy traffic loads and extreme tropical weather exposure. Such damage not only reduces driving comfort but also increases the risk of traffic accidents, particularly for two-wheeled vehicles, which are more sensitive to surface irregularities. This finding is consistent with previous field reports that asphalt-based joints tend to undergo plastic deformation more quickly compared to elastomer-based joints such as SSJ (Tetiranont et al., 2024).

In contrast, SSJ demonstrated better performance in withstanding dense traffic loads and heavy vehicles. Within an observation period of up to four years, damage was limited only to rubber seal degradation and minor cracks, which could be handled with light maintenance such as epoxy filling. This condition confirms that SSJ joints have longer durability, thereby providing higher safety assurance to road users. In other words, longer maintenance intervals for SSJ not only result in cost savings but also preserve traffic stability and reduce potential safety hazards.

The following table presents a comparison of durability and safety performance between the two joint types.

Table 3 Comparison of Durability and Safety Performance of APJ and SSJ

Aspect	Asphaltic Plug Joint (APJ)	Strip Seal Joint (SSJ)
Average service life before damage	18 months	4 years
Main type of damage	Cracks, potholes, steel plate loss	Minor cracks, rubber degradation
Safety risk	High (two-wheeled vehicles vulnerable to accidents)	Low (more stable surface)
Maintenance frequency	Frequent (2–3 times within 5 years)	Rare (1 time within 5 years)
Social impact	Accidents, congestion, time loss	Minimal disturbance

Source: Field analysis, 2023

From the safety perspective, damage occurring on APJ has serious implications. Road surface potholes at the joint area can trigger single-vehicle accidents, particularly for motorcycle riders, who constitute the majority of traffic in this corridor. Moreover, untreated damage can potentially cause long queues due to partial lane closures for emergency repairs. This condition generates considerable social costs in the form of delayed goods transportation, loss of community time, and heightened risk of traffic accidents. P. Kumar et al. (2024) emphasize that safety is not merely a technical factor, but also part of social and economic sustainability. Thus, selecting a more durable and safer joint type such as SSJ can be considered a long-term investment that goes beyond mere technical efficiency.

Furthermore, this durability difference is closely related to Indonesia’s humid tropical climate, characterized by high rainfall and significant temperature fluctuations. Under such conditions, asphalt-based materials used in APJ are more susceptible to softening and thermal cracking. Conversely, SSJ, with its rubber elements and steel structure, has better flexibility to accommodate expansion and contraction due to temperature variations, thereby exhibiting higher weather resistance. This result is consistent with Lille et al. (2021), who stressed that life-cycle evaluation of materials must consider local environmental factors to ensure long-term infrastructure resilience.

From the perspective of road users, the safety assurance provided by SSJ also contributes to driving comfort. A smooth road surface without damaged joints ensures a safer and more efficient driving experience, reducing fatigue and risky maneuvers. In contrast, road users passing over damaged APJ joints often need to decelerate abruptly, which under congested conditions may lead to rear-end collisions. Therefore, joint durability should not be viewed merely as a technical issue, but also as part of efforts to create a safe and sustainable transportation system.

Another implication lies in infrastructure budgeting. Faster deterioration of APJ requires more frequent repairs, which not only increases direct maintenance costs but also produces indirect costs from traffic disruptions. This situation clearly contradicts the principle of sustainable development, which emphasizes resource efficiency and public safety protection. On the other hand, although SSJ requires higher initial investment, it yields broader benefits in terms of long-term cost savings and accident risk reduction.

Durability and safety should therefore be prioritized in the selection of bridge expansion joint types. Choosing SSJ, despite its higher initial cost, provides assurance of transport infrastructure sustainability, as it maintains optimal bridge function without imposing excessive risks on users. This perspective aligns with Hamzah & Go (2023), who argued that sustainable infrastructure design must integrate safety as a fundamental component of public service quality.

Environmental and Social Impacts of Maintenance Frequency

The frequency of expansion joint maintenance on bridges not only carries technical and financial consequences but also exerts significant environmental and social impacts. As presented in the previous field data, Asphaltic Plug Joint (APJ) requires more frequent repairs, on average every 18 months, with cumulative maintenance costs over five years amounting to Rp. 109 million. Meanwhile, Strip Seal Joint (SSJ) exhibits longer durability, lasting up to four years before intervention is needed, with significantly lower maintenance costs at Rp. 36.9 million. This difference is not merely a numerical value in a technical table but has tangible implications for the surrounding environment, road user mobility, and the socio-economic conditions of affected communities.

The high repair frequency of APJ creates a domino effect that warrants attention. Each repair requires partial road closure or traffic diversion. This condition directly causes traffic congestion, which in turn increases travel time, fuel consumption, and vehicle exhaust emissions. According to Song et al. (2022), traffic congestion in infrastructure repair zones can increase vehicle fuel consumption by up to 25% compared to normal conditions. This means that every APJ repair involves not only material and labor costs but also environmental costs borne by society in the form of additional air pollution and increased carbon footprint.

In comparison, SSJ offers greater ecological advantages due to its longer maintenance interval. With a service life of up to four years before damage occurs, required interventions are minimal. This translates into fewer traffic disruptions, reduced vehicle emissions, and preserved energy efficiency in transportation. From the perspective of green infrastructure, sustainability is not measured solely by structural strength or lower life-cycle cost, but also by the extent to which infrastructure minimizes long-term environmental impacts (Bianchi & Malki-Epshtein, 2021). Social impacts are also an important aspect often overlooked in technical analysis. When APJ deteriorates into cracks or potholes, road user safety risks increase. Potholes at the joint may cause motorcycles to lose balance or four-wheeled vehicles to suffer severe impact on wheels and suspension. Beyond accident potential, repeated repair activities also disrupt community comfort. Road users face congested routes, construction noise, and reduced travel quality.

In socio-economic terms, congestion caused by repeated repairs leads to loss of productive time. Every minute of delay on the road equates to lost labor productivity, increased logistics costs, and decreased quality of life. Deng et al. (2023) reported that economic losses from traffic congestion in Southeast Asian urban areas can reach 2–5% of annual Gross Domestic Product (GDP). Although their study focused on urban contexts, the same loss mechanism applies to repeated bridge joint repair cases, which repeatedly hinder transport mobility along strategic road corridors.

To illustrate the difference in environmental and social impacts between APJ and SSJ, the following table is presented:

Table 4 Comparison of Environmental and Social Impacts between APJ and SSJ

Aspect	Asphaltic Plug Joint (APJ)	Strip Seal Joint (SSJ)
Repair frequency	Every ±18 months (3 times in 5 years)	Every ±4 years (1 time in 5 years)
Vehicle emissions	High (due to frequent congestion)	Low (fewer disruptions)
Energy consumption	Inefficient (fuel wastage)	More efficient
Traffic disruption	High (frequent closures/disturbances)	Lower (rare maintenance)
Accident risk	High (cracks/potholes hazardous to users)	Low (stable strip seal surface)
Social costs	Large (time loss, stress, logistics burden)	Smaller
Environmental aspect	Unsustainable (high carbon footprint)	More sustainable (supports green infrastructure)

Source: Field analysis, 2023

Table 4 indicates that although APJ may appear cheaper during initial installation, its maintenance frequency produces greater environmental and social consequences. Conversely, SSJ, which requires higher upfront cost, succeeds in reducing external impacts that are often excluded from technical planning, namely social losses and environmental damage.

The concept of green infrastructure emphasizes the importance of infrastructure that minimizes maintenance interventions in order to reduce carbon footprint and limit disruption to ecosystems and communities (Washbourne, 2022). In this regard, choosing SSJ aligns more closely with the paradigm of sustainable development, since despite its higher initial investment, it proves more efficient in the long term in both environmental and social dimensions. From a societal standpoint, joint type selection is also closely related to social equity. Infrastructure that frequently fails and requires repeated repairs indirectly burdens road users, particularly those who depend daily on smooth transportation for work, trade, or access to public services. Mobility disruption translates into lost economic opportunities and heightened psychological stress due to uncomfortable travel conditions. SSJ, with its longer durability, is therefore capable of delivering a more stable, safer, and community-friendly travel quality.

Strategic Implications for Infrastructure Planning in Indonesia

The findings from the comparative performance analysis of Asphaltic Plug Joints (APJ) and Strip Seal Joints (SSJ) on the Krian–Mojokerto Toll Road Bridge carry significant strategic implications for the trajectory of infrastructure planning in Indonesia. These results extend beyond technical considerations, encompassing economic, social, and macro-policy dimensions of national development. In practical terms, the fundamental differences between APJ and SSJ provide concrete guidance for planners, contractors, and policymakers in determining the most appropriate type of expansion joint, depending on traffic conditions, budget availability, and long-term development objectives. APJ, with its lower initial costs and faster installation process, may serve as an attractive option, particularly for projects with limited budgets or temporary needs. However, the study demonstrates that SSJ is more capable of meeting the demands of bridges with heavy traffic loads and extended service life, as it is less prone to damage and entails lower life-cycle costs.

These findings align with Indonesia's pressing need to shift from an infrastructure planning orientation focused primarily on upfront costs toward a long-term sustainability approach. For decades, infrastructure projects in Indonesia have largely been designed under the logic of short-term efficiency—minimizing initial construction expenses to expedite project realization (Bigwanto et al., 2024). Yet, such an approach often yields serious consequences in the form of escalating maintenance costs, heightened safety risks, and unanticipated socio-economic burdens. In the context of expansion joints, while APJ offers savings in initial costs (IDR 2.17 million/m compared to IDR 11.45 million/m for SSJ), over a five-year period it proves more expensive due to frequent maintenance required at approximately 18-month intervals. Conversely, SSJ, though more costly upfront, proves to be more economical within a five-year horizon, requiring less intervention with maintenance intervals of up to four years. This underscores the necessity of a paradigm shift in planning processes, moving away from "cheap construction" toward "sustainable investment."

Furthermore, these results are closely aligned with Indonesia's national policy framework, which increasingly emphasizes sustainable infrastructure development. The National Medium-Term Development Plan (RPJMN) 2020–2024 explicitly underscores that infrastructure must be designed with resilience, sustainability, and fiscal efficiency in mind. This requires stakeholders to adopt life-cycle cost analysis (LCCA) in evaluating technological choices, including bridge joint systems. Given that SSJ offers higher durability, lower life-cycle costs, and superior safety performance, the study's recommendations align with national infrastructure policy priorities. SSJ, therefore, should be prioritized for strategic bridges, particularly along toll road corridors supporting national logistics flows, as it ensures service continuity while minimizing traffic disruptions.

Another strategic implication is the need to recalibrate Indonesia's technical standards and infrastructure development guidelines. Existing regulations, such as the Ministry of Public Works and Housing Regulation No. 11/SE/M/2015 on bridge maintenance, already emphasize the importance of inspection and asset management. However, this study provides new empirical evidence that could enrich the formulation of standards for selecting expansion joints according to traffic conditions and expected service life. In other words, research-based recommendations such as these could serve as the foundation for updating national standards, ensuring that decisions are informed not merely by initial costs but by more comprehensive technical-economic considerations.

Beyond technical and economic domains, the study highlights the significant social costs arising from inappropriate joint selection. The higher maintenance frequency of APJ often results in frequent lane closures, traffic congestion, increased vehicle emissions, and elevated accident risks. This finding resonates with Kaiser and Barstow's (2022) study, which emphasizes that the social costs of traffic disruptions in infrastructure projects may substantially outweigh the technical costs themselves. Consequently, infrastructure policy must account for such socio-economic externalities in decision-making. SSJ, with its lower maintenance frequency, emerges as the more socially sustainable option, minimizing traffic disturbances and reducing accident risks.

CONCLUSION

Based on the research findings and discussion, it can be concluded that the comparative analysis of Asphaltic Plug Joints (APJ) and Strip Seal Joints (SSJ) on the Krian–Mojokerto Toll Road Bridge provides a clear picture of the technical, economic, and sustainability implications for bridge joint system planning in Indonesia. While APJ offers practical advantages such as shorter installation time and lower upfront costs, making it suitable for emergency conditions or budget-constrained projects, its susceptibility to damage and frequent maintenance requirements increase life-cycle costs over a five-year period and pose potential safety and social burdens due to traffic disruptions. By contrast, SSJ demonstrates superior durability, longer maintenance intervals, and more cost-efficient long-term performance, positioning it as the more sustainable option for bridges with high traffic volumes and longer spans. Accordingly, this study underscores the need for a paradigm shift in infrastructure planning, from a short-term orientation based on initial costs toward a long-term orientation that prioritizes safety, life-cycle cost efficiency, and environmental sustainability. The novelty of this study lies in its comparative approach, which systematically integrates technical, economic, and environmental dimensions within a tropical, high-traffic context, thereby contributing practical insights for policy formulation and sustainable bridge infrastructure development in Indonesia.

ETHICAL STATEMENT AND DISCLOSURE

This study was conducted in accordance with established ethical principles, including informed consent, protection of informants' confidentiality, and respect for local cultural values. Special consideration was given to participants from vulnerable groups to ensure their safety, comfort, and equal rights to participate. No external funding was received, and the authors declare no conflict of interest. All data and information presented were collected through valid research methods and have been verified to ensure their accuracy and reliability. The use of artificial intelligence (AI) was limited to technical assistance for writing and language editing, without influencing the scientific substance of the work. The authors express their gratitude to the informants for their valuable insights, and to the anonymous reviewers for their constructive feedback on an earlier version of this manuscript. The authors take full responsibility for the content and conclusions of this article.

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