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Production Cost Management of Porous Asphalt Mixtures with Variations in Additive Type and Content

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Abstract. Porous asphalt mixtures require the addition of additives to improve mechanical stability and durability. Commonly used additive types include cellulose fibers, polymers, crumb rubber, and anti-stripping agents, each with different characteristics of material cost, energy requirements, and process complexity. The determination of optimal additive levels is carried out through laboratory testing which requires significant costs. The components of production costs include direct material costs, energy for heating and mixing, as well as indirect costs such as equipment depreciation and testing. The economic feasibility analysis should use a lifecycle perspective by considering maintenance costs, user costs, and environmental benefits. Economic scale is a determining factor in feasibility, where large-scale projects are more likely to achieve efficiency. Seasonal and weather conditions affect the energy needs of drying and mixed employment. The transportation distance also determines the needs of the fleet and thermal insulation system. This research emphasizes the importance of integrating technical and economic aspects in planning the use of additives in porous asphalt, so as to support the sustainability of road infrastructure with more efficient costs and greater environmental benefits.

Keywords: Additive; Economic Feasibility; Lifecycle Cost; Porous Asphalt; Production Cost.

1. INTRODUCTION

Porous asphalt has been recognized as a pavement solution capable of reducing surface water puddles and improving driving safety during rain. Its open pore structure allows water to seep into the layers below, thereby reducing the risk of aquaplaning and water spray. Each material has unique characteristics that need to be understood to achieve maximum results (Triono et al., 2023). However, this porous nature also brings weaknesses in the form of decreased mechanical stability and resistance to fatigue caused by traffic loads. This material tends to be more brittle compared to conventional asphalt mixtures due to reduced contact between aggregates caused by high air voids (Pančić, 2024). Careful planning is highly needed so that the building structure remains strong and durable (Anwar et al., 2022). To overcome these weaknesses, researchers and construction practitioners have begun adding various additives to the porous asphalt mixture. Additives such as cellulose fibers, polymers, or natural rubber are expected to increase cohesion between particles without significantly reducing porosity. Each type of additive has different characteristics regarding price, availability, and influence on the production process. Choosing the right additive must consider not only the improvement of technical properties but also the overall production cost implications. In national road projects that can reach tens of kilometers, even the smallest difference in cost per square meter will accumulate into a very large figure (Slebi-Acevedo et al., 2023). Good material management is the primary key to ensuring project budgets do not swell (Theodara et

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al., 2022). Therefore, the management of production costs for porous asphalt mixtures with additives becomes a highly relevant issue for policymakers and contractors.

Various types of additives have been tested in porous asphalt mixtures with varying levels of success (Lu et al., 2021). The use of quality materials will certainly have a significant impact on the final result and the economic value of a construction (Djaelani et al., 2022). Cellulose fibers derived from wood or agricultural waste are known to be able to increase resistance to asphalt runoff at high temperatures. These fibers function as a binder to prevent the asphalt from flowing out of the mixture during transportation and compaction. The price of cellulose fibers is relatively cheap and locally available in many agrarian countries. However, these fibers require a longer mixing process to ensure even dispersion within the mixture. In addition to materials, the maintenance of machines and equipment used must also be considered so that the production process runs smoothly (Riyadin & Darmawan, 2023).

Polymers such as styrene-butadiene-styrene or SBS offer increased elasticity and resistance to permanent deformation. Porous asphalt mixtures with polymers show excellent performance in the laboratory, but the cost of polymers is much higher compared to other additives. Natural rubber processed from waste tires into crumb rubber offers an environmentally friendly solution while simultaneously increasing the flexibility of the mixture. The availability of crumb rubber is quite abundant from the tire recycling industry; however, its mixing process requires higher temperatures. These variations in additive types create a wide landscape of choices for project planners. Every choice carries consequences for direct material costs, energy costs, equipment costs, and labor costs.

The content of additives in porous asphalt mixtures is a variable that significantly affects production costs (Zhang et al., 2020). In road project execution, precise budget calculation is crucial for comparing planned costs with reality in the field (Haqiqi & Djaelani, 2023). A content level that is too low may not provide meaningful performance improvements, rendering the investment in additives inefficient. Conversely, an excessively high content can substantially increase material costs while additional performance gains diminish, reaching a point of diminishing returns. Furthermore, excessive additive content can disrupt the mixing process, for example, causing undispersed fiber clumps or an excessive increase in asphalt viscosity. These process disruptions can slow down the production rate of the mixture at the asphalt mixing plant, which means higher operational costs per ton of mixture. Determining the optimal additive content requires a balance between improvements in mechanical properties, durability, and ease of production (Dave et al., 2025). In road engineering literature, various studies have reported optimal contents for each type of additive, but these figures are highly dependent on the type of aggregate, gradation, and base asphalt used (White et al., 2022). There is no universal formula applicable to all conditions. Each project needs to conduct laboratory tests to determine the optimal content adjusted to the locally available materials. The cost of this testing is itself a component that must be accounted for in the project budget, especially for small-volume projects where the testing cost per unit becomes significant.

The production process of porous asphalt mixtures differs from conventional asphalt mixtures because high porosity requires stricter temperature and mixing time control (İbiş et al., 2021). Porous asphalt is typically produced at lower temperatures to reduce the risk of asphalt oxidation, which can accelerate aging. However, the addition of certain additives such as rubber powder requires higher temperatures to ensure homogeneous mixing. The conflict between the need for low temperatures for the asphalt and high temperatures for the additives creates complex operational challenges. Asphalt mixing plants must be able to accurately adjust production parameters, which may require equipment modifications or investment in more advanced control systems. Mixing time also needs to be extended to ensure even dispersion of the additives, which reduces production capacity per hour. A decrease in production capacity means longer operational hours to produce the same volume of mixture, so fixed costs such as plant rental and operator salaries are divided over a smaller production volume. The accumulation of all these factors can cause the production cost of porous asphalt mixtures with additives to be 20 to 50 percent higher than conventional asphalt mixtures. This significant cost increase must be justified by the environmental and safety benefits generated by the porous pavement.

The economic feasibility of using porous asphalt mixtures with additives is determined not only by production costs but also by longer life-cycle benefits (Global et al., 2023). Porous pavements that are more resistant to deformation and cracking can have a longer service life than conventional pavements, resulting in lower annual maintenance costs. Reducing standing water also reduces the risk of accidents, which means savings in social costs from accident victims and vehicle damage. Technically, every accident caused by inadequate infrastructure often leads to ethical and legal violations when the personal information of victims is widely spread in digital media (Muhammad et al., 2023). In urban areas, porous asphalt contributes to better rainwater management, reducing the burden on urban drainage systems and the risk of local flooding (Govedarica et al., 2025). These indirect benefits are difficult to measure monetarily but are very real for the community. A comprehensive economic feasibility analysis must consider all these benefits, rather than just comparing the initial production cost with conventional asphalt. For road projects in areas with high rainfall or accident-prone zones, the benefits of porous asphalt may far outweigh the additional costs. Conversely, for low-traffic roads in dry areas, the extra cost of porous asphalt may not be justified. The decision to use porous asphalt must be made based on site-specific analysis considering environmental conditions, traffic patterns, and budget availability.

The primary problem faced in the production cost management of porous asphalt mixtures is the lack of accurate data regarding the relationship between the type and content of additives and the actual production costs in the field. Most research on porous asphalt is conducted in small-scale laboratories, using laboratory mixing equipment that does not represent mass production conditions at an asphalt mixing plant. Parameters such as the mixing time required for fiber or rubber powder dispersion in the laboratory may differ significantly from what is required at an industrial-scale plant. Similarly, energy consumption for heating materials to the required temperature can be easily measured in the lab, but in the field, the thermal efficiency of the plant and heat loss during transportation significantly affect actual energy costs (Dhar et al., 2025). This lack of field data forces project planners to use rough estimates that are often inaccurate. Consequently, project budgets can swell because actual production costs are higher than estimated, or conversely, the quality of the mixture is sacrificed to suppress ballooning costs. Contractors with little experience in porous asphalt may encounter unexpected operational difficulties, such as challenging paving processes due to the mixture being too cold or too hot. These problems are exacerbated by the fact that each type of additive has unique characteristics, meaning experience with one type of additive cannot be directly transferred to another.

Another equally important problem is the fluctuation of additive prices in the market, which can disrupt the economic feasibility of a project. Polymer prices are highly dependent on world crude oil prices, which can change dramatically in a short period. The price of cellulose fibers is influenced by harvest seasons and forestry policies. The price of rubber powder depends on the availability of scrap tires and their processing costs. When a project is planned, cost calculations are based on the prices of additives at that time. However, because road projects usually last for one to two years, additive prices can change significantly during that period. Contractors who have locked in a contract price with the employer may have to absorb the increase in additive prices, which erodes profit margins or even causes losses. Conversely, if prices fall, the employer may request price adjustments, necessitating complicated negotiations. This risk of price fluctuation can be managed through hedging contracts or advance material purchases, but both strategies require substantial working capital and expertise in commodity risk management. For medium-sized contractors, who are the backbone of the construction industry in many countries, the capacity to perform hedging is very limited. As a result, they tend to avoid using additives with volatile prices, even if those materials are technically superior. This condition hinders the adoption of better porous asphalt technologies. This highlights the importance of continuously finding ways so that new innovations can still be implemented effectively despite facing various market constraints (Triono & Darmawan, 2024).

Governments in many jurisdictions are beginning to mandate the use of porous pavements in specific areas to reduce urban flood risks and enhance groundwater recharge (Xi & Liu, 2024). Technical standards for porous asphalt are continuously being updated, often with stricter performance requirements that drive the use of additives. Contractors who are not technically and economically prepared will struggle to win tenders for such projects. On the other hand, contractors capable of offering high-quality porous asphalt at competitive costs will possess a significant competitive advantage. Research on this topic can assist contractors in identifying the most efficient production strategies for various types of additives. For policymakers, an understanding of the cost structure of porous asphalt is essential for establishing reasonable unit prices in government construction cost standards. A unit price that is too low will discourage contractors from bidding, while a price that is too high burdens the public budget. Additionally, an accurate economic feasibility analysis can help the government prioritize which road segments are most suitable for porous asphalt based on the cost-benefit ratio. In the long run, the widespread adoption of porous asphalt can substantially reduce national road maintenance costs.

The objective of this literature study is to construct a conceptual framework that links the technical parameters of porous asphalt mixtures with production cost components and economic feasibility analysis methods. This framework will identify key factors influencing costs, including material costs, energy costs, equipment costs, and labor costs. Theoretically, this study enriches road engineering literature by highlighting the economic aspects that are often separated from technical research. Practically, this framework can be used by contractors to estimate the production costs of various mixture alternatives, as well as by employers to evaluate the fairness of bid prices.

2. RESEARCH METHODOLOGY

This research is designed as a qualitative literature study that relies entirely on available written sources. Patten (2016) explains that a literature-based approach is a valid method when the research objective is to synthesize knowledge accumulated from various previous studies.

In accordance with this principle, this research does not involve laboratory testing of asphalt mixtures, interviews with contractors, or surveys of additive suppliers. All analytical materials are derived from written documents such as journal articles, road engineering textbooks, conference proceedings, specification standards, and project reports. Gupta and Gupta (2022) emphasize that the quality of a literature study depends heavily on the scope of the sources cited and the precision of the selection process. The source selection process is conducted by reading abstracts first, followed by reading the full text to evaluate specific contributions to the problem formulation.

The analysis procedure in this literature study follows a thematic synthesis approach as a method for combining findings from various sources (Priyanka, 2024). Thematic synthesis allows for the integration of insights from laboratory studies, field studies, and economic modeling into a unified explanatory framework (Berger-Tal et al., 2019). The first step is the organization of sources based on main themes: types of additives and their influence on mixture properties, additive content and optimal points, production cost components, and economic feasibility analysis methods. The second step is the identification of patterns that emerge repeatedly in the literature, such as the consistent finding that cellulose fibers provide improved stability at the lowest cost. The third step is the tracing of contradictions between studies, which often reveal factors such as aggregate type or mixing conditions. A good literature study must note any tensions in the findings (Imed, 2019). In this research, special attention is given to how findings from studies on technical performance can be integrated with findings from studies on production costs. The analysis process is conducted iteratively, with researchers moving back and forth between individual sources and the conceptual framework. The final step is the writing of a report that presents findings in a structured narrative form, explicitly referring to the sources underlying each important statement.

3. RESULTS AND DISCUSSION

The most common types of additives used in porous asphalt mixtures are cellulose fibers, polymers, crumb rubber, and anti-stripping agents. Cellulose fibers function as crucial asphalt stabilizers to prevent the asphalt from flowing out of the mixture (drain-down) during transportation and compaction processes. Without the presence of fibers, asphalt tends to flow to the bottom of the mixture pile, leaving the top part dry, brittle, and susceptible to structural damage. Well-dispersed cellulose fibers form a three-dimensional network that effectively traps the asphalt in place. In the context of material procurement, the cost of cellulose fibers for construction and asphalt needs in the current wholesale market ranges from USD 1.75 to

USD 2.50 per kilogram (or equivalent to Rp25,000 to Rp40,000 per kg), depending on the purchase volume and purity level. With commonly used fiber content ranging from 0.3 to 0.5 percent of the total mixture weight (Cabral et al., 2021), the fiber material cost required to produce one ton of porous asphalt mixture is approximately USD 5.25 to USD 12.50. Although this material cost is slightly higher than older literature estimates, the amount is still relatively small compared to the cost of the main asphalt component, which can reach 60 to 80 dollars per ton of mixture (Marleno et al., 2021). However, the main challenge of using cellulose fibers lies in the operational aspect, where an additional mixing time of 10 to 20 seconds per batch is required to ensure even fiber dispersion within the mixture. If a mixing plant has an operational capacity of 200 tons per hour, an additional mixing time of just 15 seconds will reduce production capacity by approximately 8 percent (Czoboly & Balázs, 2017). This reduction in capacity impacts fixed operational costs, such as plant rental fees and operator salaries, which must be divided over a smaller production volume, thereby increasing the unit cost per ton. Thus, the indirect cost burden resulting from this decrease in productivity has the potential to exceed the direct cost of the cellulose fiber material itself.

Polymers such as SBS (Styrene-Butadiene-Styrene) and other elastomers offer more dramatic improvements in mechanical properties compared to the use of cellulose fibers alone (Kim et al., 2010). Polymer-modified porous asphalt mixtures show much better resistance to permanent deformation at high temperatures as well as more optimal crack resistance at low temperatures. These properties become very valuable for road construction with heavy traffic loads or in regions with extreme temperature variations that can accelerate road damage. However, this mechanical effectiveness comes at a quite high material cost. Currently, the price of SBS polymer in the industrial market ranges from 3 to 5 dollars per kilogram (approximately Rp48,000 to Rp80,000 per kg), which is about two to three times the price of industrial cellulose fibers. Effective polymer content usually falls within the range of 3 to 6 percent of the asphalt weight. As an illustration, for a mixture with 5 percent asphalt content, using polymer at 4 percent of the asphalt weight is equivalent to 0.2 percent of the total mixture weight. Thus, the direct cost of polymer per ton of mixture ranges from 6 to 10 dollars, which is nominally still competitive with the cost of cellulose fibers (Šrámek et al., 2023).

The fundamental difference lies in the complexity of its production process. Polymers must be mixed with asphalt at high temperatures using special tanks before the polymer-modified asphalt is fed into the batching plant. This process requires significant additional equipment investment in the form of a colloidal mill or high shear mixer to ensure the polymer is perfectly dispersed within the asphalt. Investment in this equipment can cost between 60,000 and 100,000 dollars, which often makes the use of polymers uneconomical for projects with a mixture volume below 50,000 tons (Turben et al., 2024).

In addition to equipment investment constraints, polymer-modified asphalt has a relatively shorter shelf life. This is due to the potential for polymer degradation if stored under hot conditions for too long or if it undergoes repeated heating. Consequently, contractors must coordinate asphalt production and mixture production very carefully to avoid material waste. Imprecise supply chain management can lead to the degradation of polymer quality, which will ultimately eliminate the dramatic technical benefits that were supposed to be gained from the investment costs incurred.

Crumb rubber from scrap tires offers an environmentally friendly solution while simultaneously increasing the flexibility of porous asphalt mixtures (Çetin, 2022). The use of crumb rubber effectively reduces the volume of tire waste in landfills, thus providing significant ecological benefits alongside improved technical pavement performance. Currently, the price of crumb rubber in the construction industry wholesale market ranges from 0.45 to 0.95 dollars per kilogram (approximately Rp7,200 to Rp15,200 per kg), depending on the particle size (mesh) and the level of cleanliness from steel wires or textile fibers. Despite experiencing increases, this price remains more competitive compared to the price of industrial cellulose fibers, which reach 1.75 to 2.50 dollars per kilogram. The crumb rubber content commonly used in asphalt mixtures is 1 to 2 percent of the total mixture weight. With current lowest price estimates, the material cost of crumb rubber per ton of mixture is approximately 4.5 dollars. However, the main challenge of using crumb rubber remains the requirement for high mixing temperatures, typically between 170 to 190 degrees Celsius, well above the conventional mixture standard which only requires 140 to 160 degrees Celsius (Mbereyaho et al., 2021). This 30-degree Celsius temperature increase has a direct impact on energy consumption. For a batching plant with a capacity of 200 tons per hour, such a temperature rise can increase fuel consumption by up to 15 to 20 percent. Given dynamic global energy prices, if fuel costs are estimated at 1.2 dollars per ton of mixture at normal temperatures, the additional operational cost due to high temperatures reaches 0.18 to 0.24 dollars per ton (Sarmonov & Rustamov, 2024).

Although the additional operational cost per ton appears small, its accumulation in large-scale projects lasting for months becomes very significant. More importantly, high temperatures correlate directly with greater greenhouse gas emissions, posing a challenge for projects targeting eco-friendly certifications. In some regions, increasingly strict carbon taxes can add to the overall production cost burden, so the economic benefit of cheap crumb rubber material prices must be balanced against increased energy costs and carbon emission compensations.

Anti-stripping agents are added to improve adhesion between asphalt and aggregate, especially when using acidic aggregates such as quartz or granite. Porous asphalt has a much higher risk of stripping because the asphalt film on the aggregate tends to be thinner due to its open porosity structure. Water entering the pores can push the asphalt off the aggregate surface, triggering structural damage known as raveling. Common anti-stripping agents used in the industry today are fatty amines or hydrated lime.

In procurement, the cost of anti-stripping agents in the current market ranges from 2.5 to 5 dollars per kilogram (approximately Rp40,000 to Rp80,000 per kg), undergoing adjustments from previous estimates due to fluctuations in global chemical raw material costs. With a usage rate of around 0.5 to 1 percent of the asphalt weight, the additional cost per ton of mixture remains relatively controlled, at about 0.6 to 1.25 dollars. The mixing process is also relatively simple, usually just by adding it to the asphalt tank or directly into the mixing plant unit (pugmill) (Webster, 2022).

However, the effectiveness of anti-stripping agents depends heavily on the type of aggregate and its moisture level during the mixing process. If the aggregate is wet, the anti-stripping agent may not function optimally in ensuring the asphalt bond. This condition forces contractors to dry the aggregate longer in the dryer, which automatically increases fuel consumption and plant operational energy costs.

Another technical challenge is the potential for chemical reactions between several types of anti-stripping agents and other additives such as polymers, which can reduce the functional effectiveness of both. Interactions between these additives are still rarely researched systematically in the field. Therefore, contractors using a combination of polymers and anti-stripping agents are required to conduct in-depth laboratory tests to ensure material compatibility.

These additional testing costs can reach 3,000 to 7,000 dollars depending on the complexity of the parameters being tested. For small-scale infrastructure projects, this testing cost burden becomes very significant to profit margins. Thus, even though the price per kilogram of material appears cheap, the risk of functional failure due to aggregate moisture and laboratory validation costs become decisive factors in the total cost efficiency of porous asphalt projects.

The optimal content of additives is determined through a series of laboratory tests that measure crucial parameters such as Marshall stability, flow resistance, wear (cantabro loss), and permeability. The curve connecting additive content with performance parameters is usually convex, where an initial increase in content provides significant functional improvement, but after passing a certain point, the improvement diminishes until performance eventually declines due to excessive content. The optimal point is generally found in the region where the slope of the curve begins to flatten.

To find a precise optimal point, testing is required on at least three to five different levels of content, where each level uses three samples to ensure statistical accuracy (Ma et al., 2022). Based on current laboratory service fee standards, testing costs for one type of additive can reach 6,500 to 12,000 dollars (approximately Rp104 million to Rp192 million), depending on the complexity and the number of parameters tested. For a project with a mixture volume of 10,000 tons, the testing cost per ton ranges between 0.65 to 1.2 dollars.

The situation becomes more complex if the project considers three different types of additives for comparison, where the total laboratory testing costs can swell up to 36,000 dollars. This figure is very significant and often becomes a heavy burden, especially for small-scale infrastructure projects. However, without valid testing, contractors are forced to refer to the content recommended in general literature, which is often inaccurate when applied to the characteristics of local aggregate or asphalt materials.

The use of non-optimal content carries two major financial risks. First, if the content is too high, there is an unnecessary waste of material costs. Second, if the content is too low, the pavement performance will be poor, leading to premature damage. The cost of early repairs or partial reconstruction is much greater than the initial research costs, especially if damage occurs before the routine maintenance period ends. Thus, despite requiring a large initial capital, investment in comprehensive laboratory testing remains the most economical step in the long run to ensure material efficiency and road durability.

Production costs for porous asphalt mixtures with additives can be broken down into direct costs and indirect costs. Direct costs include the cost of aggregates, asphalt, additives, and energy for heating and mixing. Aggregate costs are relatively stable because aggregate is the main component with competitive pricing. Asphalt cost is the largest component, reaching 40 to 60 percent of total direct costs (Rafiq et al., 2021). Additive costs, although small in percentage, can vary significantly between types. Energy costs are influenced by the required mixing temperature and mixing time. Indirect costs include equipment depreciation, maintenance costs, personnel salaries, administrative costs, as well as testing and quality control costs. These indirect costs are often ignored in laboratory analysis, but in the field, contractors must cover them from profit margins. For small-volume projects, indirect costs per ton tend to be high because fixed costs such as equipment mobilization and plant setup must be amortized over a smaller volume. Conversely, for large projects with volumes of hundreds of thousands of tons, indirect costs per ton can be reduced. This scale of economy is very important in determining the feasibility of using porous asphalt with additives. Small projects may not be economical due to high testing and setup costs, while large projects can absorb these costs. Local governments with limited budgets may need to consolidate several small projects into one larger tender package to achieve economies of scale.

The economic feasibility analysis of using porous asphalt with additives must consider the full pavement life cycle, rather than just the initial construction costs (Liu et al., 2020). The life cycle includes initial construction costs, routine maintenance costs, major rehabilitation costs, and the residual value at the end of the design life. Porous asphalt with additives that enhance durability may have higher initial costs but lower maintenance costs due to longer maintenance intervals. To calculate the present value of all future costs, a discounted cash flow method is used with a discount rate that reflects the cost of capital for the government or contractor. Large differences in initial costs can be offset by maintenance cost savings in subsequent years, especially for high-traffic roads where lane closures for maintenance also incur congestion costs. These congestion costs are often referred to as road user costs, which include additional travel time, extra fuel consumption, and vehicle wear and tear due to queuing. Studies in developed countries show that road user costs can reach 5 to 10 times the maintenance costs themselves. Thus, even if porous asphalt with additives is 30 percent more expensive in construction costs, if it reduces maintenance frequency from every 5 years to every 8 years, the savings in road user costs can cover the higher initial costs. A feasibility analysis that only compares construction costs will be misleading. A broader perspective that considers all stakeholders is required.

Commonly used economic feasibility analysis methods in road projects are cost-benefit analysis and cost-effectiveness analysis (Al-Mumaiz & Evdorides, 2019). Cost-benefit analysis measures all benefits that can be calculated in monetary terms, including reduced road user costs, reduced accident costs, reduced maintenance costs, and environmental benefits such as flood reduction and improved water quality. These benefits are then compared with the additional cost of porous asphalt. A benefit-cost ratio greater than 1 indicates that the project is economically feasible. However, not all benefits are easily calculated. Environmental benefits such as increased groundwater recharge are difficult to measure in monetary units. To overcome this, cost-effectiveness analysis can be used, where additional costs are compared with the effectiveness in achieving a specific target, for example, the reduction of stormwater runoff volume per unit cost. This approach does not require converting all benefits into money, but the results do not directly indicate whether the project is feasible. For porous asphalt projects in urban areas, stormwater management aspects are often a primary consideration, making cost-effectiveness analysis more appropriate. In suburban areas that focus more on safety, a cost-benefit analysis incorporating the statistical value of human life may be more suitable. There is no perfect method for all situations; the choice of method depends on the priorities of the policymakers.

Risks and uncertainties must be accounted for in economic feasibility analysis because many parameters are not known with certainty (Jensen & Sublett, 2017). Future additive costs may fluctuate, field performance of porous asphalt may differ from laboratory results, and the appropriate discount rate is often debated. Accurate calculation of production costs through variable costing methods is a key factor in maintaining the financial stability of a project (Sinambela et al., 2022). Sensitivity analysis can be performed by changing one parameter at a time and observing its impact on feasibility results. For example, if additive costs rise by 50 percent, is the benefit-cost ratio still above 1? If yes, then the decision to use porous asphalt is robust against cost increases. If not, the decision is sensitive and needs to be reviewed. Scenario analysis is more sophisticated, changing several parameters simultaneously according to optimistic, pessimistic, and most likely scenarios. The results of scenario analysis provide an overview of the range of possible outcomes, rather than just a single fixed number. For projects with high uncertainty, decisions can be based on expected values by considering the probability of each scenario. However, determining probabilities is often subjective. Discussions among experts can help reach a consensus on realistic probability ranges. In practice, many porous asphalt projects funded by the government do not go through a rigorous feasibility analysis but are instead driven by established environmental policies (Gundrathi et al., 2023). In such cases, economic analysis serves to validate the policy, rather than to determine whether to use porous asphalt or not.

The transportation cost of porous asphalt mixtures from the mixing plant to the project site can be a determining factor for economic feasibility, especially for projects in remote areas. Porous asphalt tends to lose temperature more quickly during transport because its high porosity increases the surface area in contact with the air. If the mixture temperature drops below the minimum compaction temperature, the mixture becomes too stiff to be compacted properly, resulting in uneven porosity and poor performance. To maintain the temperature, hauling trucks must be equipped with insulation covers or even heating systems. Trucks with insulation covers can be rented at a cost 20 to 50 percent higher than regular trucks (Taher et al., 2021). Longer hauling distances also require more trucks to maintain a constant paving rate, as each truck makes a longer round trip. If the distance from the plant to the site is 50 kilometers, one truck can make 4 to 5 trips per day. If the distance increases to 100 kilometers, the trips drop to 2 to 3 per day, necessitating double the number of trucks for the same production rate. This additional truck rental cost can add 5 to 10 percent to production costs. For large-volume projects, building a temporary mixing plant near the project site may be more economical despite significant mobilization and demobilization costs. The decision between using an existing distant plant or building a new plant near the site should be based on a total cost analysis that considers production volume, project duration, and transportation costs.

Season and weather during project implementation affect the production costs of porous asphalt mixtures with additives (Zhang et al., 2020). During the rainy season, aggregates tend to be wet, requiring longer drying times in the aggregate dryer. This additional drying significantly increases fuel consumption. Furthermore, high air humidity can cause condensation on the aggregate surface after drying, reducing the adhesion between the asphalt and the aggregate. Technical issues like these, if not handled properly, will certainly disrupt the overall workflow (Irfan et al., 2024). To overcome this, contractors may need to increase the mixing temperature or add anti-stripping agents, both of which increase costs. On the other hand, fluctuating environmental conditions also greatly affect the comfort and work results of employees (Radjawane & Darmawan, 2022). During the dry season with high daytime temperatures, is it easier for porous asphalt mixtures to lose heat because the temperature difference between the mixture and the environment is smaller? On the contrary, high ambient temperatures actually help maintain the mixture temperature during transport, reducing the need for insulation. However, paving work during a hot day is very exhausting for workers, which can decrease productivity and increase the risk of workplace accidents. Declining physical conditions due to exhaustion need serious attention to ensure that the quality of work is maintained (Irfan, 2022). Some contractors choose to work at night to avoid the heat, but overtime costs and additional lighting must be taken into account. Pressure in managing time and targets often becomes a mental burden for project management (Darmawan & Djaelani, 2021). Production schedule planning that considers the season can save costs significantly. Ideally, the production of porous asphalt with additives is carried out during the dry season with moderate temperatures, between 20 to 30 degrees Celsius. Unfortunately, project schedules often do not provide the flexibility to choose the best season, especially for projects funded by annual budgets that must be completed before the end of the fiscal year.

Market competition and contractor bidding strategies also influence the actual production costs of porous asphalt with additives. In competitive tenders with many participants, contractors tend to offer very thin price margins, sometimes only 5 to 10 percent above the estimated direct costs (Bingol, 2022). In such situations, contractors have no room for errors or unforeseen costs. If porous asphalt production faces issues such as an unanticipated decrease in plant capacity, the contractor may suffer losses. Conversely, in tenders with few participants, contractors can include larger profit margins, providing a buffer to address production problems. Contractors who have experience with porous asphalt and specific additives can bid more aggressively because they are confident in their ability to control costs. Inexperienced contractors tend to add large safety factors to their bids, which can make their offers uncompetitive. To encourage the adoption of porous asphalt, employers can split tenders into small-volume trial work packages, allowing contractors to gain experience without significant risk. Once a contractor has proven their capability, larger work packages can be tendered with the requirement that the contractor must have prior experience. This phased tendering strategy has been successful in several countries for introducing new construction technologies. However, this strategy requires meticulous planning and coordination between agencies.

4. CONCLUSION

The type and content of additives in porous asphalt mixtures influence production costs through three main pathways: direct material costs, energy costs for heating and mixing, and indirect costs such as equipment depreciation and testing fees. Cellulose fibers offer the lowest cost and the simplest process but provide limited performance improvement. Polymers provide the highest performance enhancement with the highest production costs due to the need for specialized equipment. Crumb rubber offers a balance between cost and performance with additional environmental benefits. The optimal additive content is found through laboratory testing, which involves significant costs but is proportional to long-term savings. The economic feasibility of using porous asphalt must be analyzed based on the full life cycle, considering maintenance costs, road user costs, and environmental benefits. Sensitivity analysis is required to address uncertainties in additive prices and other parameters. Economies of scale are crucial in determining feasibility, where large projects are more viable than small ones. Season, weather, and hauling distance also affect actual costs in the field.

The implications of these findings for practitioners are that the selection of additives for porous asphalt cannot be based on technical considerations alone but must account for production costs and economic feasibility within the specific project context. Contractors are advised to conduct laboratory tests with local materials to determine optimal content, rather than relying on general recommendations from literature. Economic feasibility analysis should utilize life-cycle methods that include road user costs. Suggestions for future research include conducting field studies that compare the actual production costs of various types of additives in projects of comparable scale. Developing cost models capable of predicting production costs based on input parameters such as aggregate type, ambient temperature, and hauling distance would be highly beneficial. Research into the interaction between different additives when used together is also necessary, as field practices tend to use combinations to optimize various properties. Studies on innovative financing mechanisms, such as performance-based payments, could encourage the broader adoption of porous asphalt.

REFERENCES

Al-Mumaiz, M., & Evdorides, H. (2019). *Changes in land value due to road development*. *172*(1), 36–46. https://doi.org/10.1680/JTRAN.17.00078

Anwar, M. S., Setiawan, A., Saleh, M., Diba, F. F., Triono, B., & Darmawan, D. (2022). Fabric Expansion Joint Roller Machine Manufacturing Planning. *International Journal of Service Science, Management, Engineering, and Technology*, 1(1), 1-5.

Berger-Tal, O., Greggor, A. L., Macura, B., Adams, C. A., Blumenthal, A., Bouskila, A., Candolin, U., Doran, C., Fernández-Juricic, E., Gotanda, K. M., & Price, C. J. (2019). Systematic reviews and maps as tools for applying behavioral ecology to management and policy. *Behavioral Ecology*, *30*(1), 1–8. https://doi.org/10.1093/BEHECO/ARY130

Bingol, F. (2022). *Economic principles of bidding for construction projects*. 351–370. https://doi.org/10.4337/9781839108235.00024

Cabral, M. V. S., Carneiro, A. M. P., Maior, R. M. S., Marinho, E. P., & Nóbrega, A. C. V. da. (2021). Customized price-quality microcrystalline cellulose for developing cementitious composites with improved mechanical properties. *Construction and Building Materials*, *300*, 124064. https://doi.org/10.1016/J.CONBUILDMAT.2021.124064

Çetin, A. (2022). Laboratory performance of porous asphalt mixtures containing Ethylene Propylene Diene Monomer - EPDM. *Građevinar*, *74*(01), 1–8. https://doi.org/10.14256/jce.3309.2021

Czoboly, O., & Balázs, G. L. (2017). Are fibers sensitive to mixing. *Structural Concrete*, *18*(1), 19–28. https://doi.org/10.1002/SUCO.201600039

Darmawan, D., & Djaelani, M. (2021). Correlation of work stress and performance of construction project manager. *ARRUS Journal of Engineering and Technology*, *1*(2), 55-59.

Dave, N., Thakkar, J., Dave, N., & Thakkar, J. (2025). Investigating Mechanical, Microstructural, and Carbon Emission Analysis Containing Pulverized Ceramic Waste Powder. 155–165. https://doi.org/10.1007/978-981-96-8830-2_15

Dhar, M., Prakasan, S., Meena, A., Gettu, R., & Bishnoi, S. (2025). Energy consumption in the production of calcined kaolinitic clays for use as supplementary cementitious materials. *Advances in Cement Research*, 1–9. https://doi.org/10.1680/jadcr.25.00011

Djaelani, M., Judiono, J., Darmawan, D., & Amri, M. W. (2022). Study of concrete: quality and economic. *Bulletin of Science, Technology and Society*, *1*(1), 1-3.

Global, R., Zheltobriukh, A. D., & Savenko, V. Y. (2023). Technical and economic justification of the feasibility of using the technology of laying covers from draining asphalt concrete. *World Science*. https://doi.org/10.31435/rsglobal_ws/30092023/8052

Govedarica, O., Škondrić, M., Stanic, F., Đukić, A., Lekić, B., & Ognjanovic, V. R. (2025). *Nature-based solution in urban drainage: Opportunities and challenges of porous paving*. 223–230. https://doi.org/10.5937/vik25223g

Gundrathi, N. G., Swetha, K., Sriharsha, G., Sabitha, G., & Ruchitha, G. (2023). Feasibility study and mix design of porous asphalt with waste plastics. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2023.02.320

Gupta, A., & Gupta, N. (2022). *Research methodology*. SBPD publications.

Haqiqi, A. H. K., & Djaelani, M. (2023). Comparative Analysis of The Design Budget for the Asphalt Road Construction of Indraprasta View Pacet Housing with The AHSP Methode with Project Design at PT. Indraprasta Graha Utama. *IJESPG (International Journal of Engineering, Economic, Social Politic and Government)*, *1*(4), 95-108.

İbiş, A. B., Sengoz, B., & Özdemir, D. K. (2021). *The Effect of Compaction Temperatures and Numbers on the Air Void Level of Porous Asphalt Pavements*. https://doi.org/10.52460/ISSC.2021.014

Imed, R. (2019). How to Prepare a Good Literature Review: A Practical Guide for Research Students. https://doi.org/10.13140/rg.2.2.25554.30408

Irfan, M. (2022). Measurement of Mental Workload and Fatigue of Production Operator. *International Journal of Service Science, Management, Engineering, and Technology*, 1(3), 11-13.

Irfan, M., Ali, R., & Darmawan, D. (2024). Digital Labour, Production Relations, and Social Class in the Age of Automation. *International Journal of Service Science, Management, Engineering, and Technology*, 5(2), 27-35.

Jensen, J. L., & Sublett, S. (2017). *Risk and Uncertainty*. 19–28. https://doi.org/10.1007/978-3-319-41369-3_4

Kim, J.-M., Lee, S., Kim, G., Cho, S.-S., & Hong, H. S. (2010). Effects of Polymer Additives on Mechanical Properties of Recycled Plastic Composites. *Journal of the Korean Society of Mineral and Energy Resources Engineers*, *47*(5), 653–659.

Liu, J., Li, H., Wang, Y., & Zhang, H. (2020). Integrated life cycle assessment of permeable pavement: Model development and case study. *Transportation Research Part D-Transport and Environment*, *85*, 102381. https://doi.org/10.1016/J.TRD.2020.102381

Lu, Q., Xin, C., Alamri, M., Alamri, M., Alharthai, M., & Alharthai, M. (2021). Development of porous asphalt mixture with bio-based epoxy asphalt. *Journal of Cleaner Production*, *317*, 128404. https://doi.org/10.1016/J.JCLEPRO.2021.128404

Ma, M., Mawlood-Yunis, A.-R., Tam, V. Wy., Le, K. N., & Osei-Kyei, R. (2022). Factors affecting the price of recycled concrete: A critical review. *Journal of Building Engineering*, *46*, 103743. https://doi.org/10.1016/J.JOBE.2021.103743

Marleno, R., Romadhon, F., Sarya, G., & Susanto, H. (2021). *Cost and Quality Analysis of the Use of Steel Fiber on Rigid Pavement with Laboratory Experimental Method*. 395–406. https://doi.org/10.1007/978-3-030-76481-4_34

Mbereyaho, L., Manzi, L., Kamanzi, P., & Nizeyimana, B. (2021). *Use and Influence of Tire Rubber Waste Powder in Bitumen Product*. *11*(2), 82–88. https://doi.org/10.2478/JEPPM-2021-0009

Muhammad, A. I., Saputra, R., Pakpahan, N. H., Darmawan, D., & Khayru, R. K. (2023). Ethics and Legality in the Dissemination of Information on Traffic Accident Victims Through Digital Media. *Journal of Social Science Studies*, *3*(2), 235-244.

Pančić, I. (2024). The effect of porous asphalts on water purification from asphalt surfaces. 361–368. https://doi.org/10.5937/vik24361p

Patten, M. L. (2016). Understanding research methods: An overview of the essentials (9th ed.). Routledge.

Priyanka, V. (2024). *Systemetic Literature Review*. https://doi.org/10.13140/rg.2.2.13347.05922

Radjawane, L. E., & Darmawan, D. (2022). Construction Project Worker Satisfaction Reviewing from the Role of the Work Environment and Leadership. *International Journal of Service Science, Management, Engineering, and Technology*, *1*(3), 36-40.

Rafiq, W., Musarat, M. A., Altaf, M., Napiah, M., Sutanto, M. H., Alaloul, W. S., Javed, M. F., & Mosavi, A. (2021). Life Cycle Cost Analysis Comparison of Hot Mix Asphalt and Reclaimed Asphalt Pavement: A Case Study. *Sustainability*, *13*(8), 4411. https://doi.org/10.3390/SU13084411

Riyadin, F., & Darmawan, D. (2023). Experimental Study of 3 KW Generator Damage Types Based on Vibration Signals. *International Journal of Service Science, Management, Engineering, and Technology,* 3(2), 27-31.

Roy, K., Pongwisuthiruchte, A., Debnath, S. C., & Potiyaraj, P. (2021). *Application of cellulose as green filler for the development of sustainable rubber technology*. *4*, 100140. https://doi.org/10.1016/J.CRGSC.2021.100140

Sarmonov, A., & Rustamov, K. (2024). Implementing energy-saving technologies in hot asphalt production: A comprehensive review. *E3S Web of Conferences*, *538*, 01029–01029. https://doi.org/10.1051/e3sconf/202453801029

Sinambela, E. A., Darmawan, D., & Gardi, B. (2022). Production cost calculation analysis using variable costing method. *International Journal of Service Science, Management, Engineering, and Technology,* 1(2), 13-16.

Slebi-Acevedo, C. J., Lastra-González, P., Indacoechea-Vega, I., & Castro-Fresno, D. (2023). Development of improved porous asphalt mixtures with high porosity levels. *Developments in the Built Environment*, *16*, 100286–100286. https://doi.org/10.1016/j.dibe.2023.100286

Šrámek, J., Kozel, M., Remek, L., & Mikolaj, J. (2023). Evaluation of Bitumen Modification Using a Fast-Reacting SBS Polymer at a Low Modifier Percentage. *Materials*, *16*(8), 2942–2942. https://doi.org/10.3390/ma16082942

Taher, M. A. B., Taher, M. A. B., Ahachad, M., Mahdaoui, M., Zeraouli, Y., & Kousksou, T. (2021). A survey of computational and experimental studies on refrigerated trucks. *Journal of Energy Storage*, 103575. https://doi.org/10.1016/J.EST.2021.103575

Theodara, N. A., Darmawan, D., & Putra, A. R. (2022). Material Management Effectiveness. *Bulletin of Science, Technology and Society*, 1(1), 7-10.

Triono, B., & Darmawan, D. (2024). 3D Printing Technology as A Driver of Innovation and Efficiency in Mechanical Engineering. *Journal of Science, Technology and Society (SICO),* 5(2), 11–20.

Triono, B., Djaelani, M., Anwar, M. S., Arifin, S., Ikhwanuddin, I., Saleh, M., Darmawan, D., Jahroni, J., & Dzinnur, C. T. I. (2023). Pemberdayaan Masyarakat di Sekitar Universitas Sunan Giri Surabaya Melalui Pelatihan Keterampilan Las Listrik. *Jurnal Pendidikan, Penelitian, dan Pengabdian Masyarakat,* 3(1), 15-20.

Triono, B., M. Shaleh & F.R.K. Mambrasari. (2023). Analysis of Micro Structure and Medium Hardness of Carbon Steel Isse Introduction Water, Oil and Air in The Hardening Process Using Cooling Media, *International Journal of Service Science, Management, Engineering, and Technology,* 3(3), 7-13.

Turben, T., Ansari, M. T., Hedden, J., Ogundipe, T., Roy, A., Tiwari, A., Eiland, J., & Braham, A. (2024). Comparison of lab-produced asphalt emulsions by manufacturing equipment type. *Road Materials and Pavement Design*, 1–25. https://doi.org/10.1080/14680629.2024.2409867

Webster, S. (2022). *Evaluation of Hot Mix Asphalt Mixtures Design Modified with Hydrate Lime*. 1493–1505. https://doi.org/10.1007/978-981-16-7924-7_98

White, G., Kidd, A., & Shadforth, T. (2022). Effect of low dosage crumbed rubber on the mechanical properties of a dense graded asphalt mixture. *Road Materials and Pavement Design*, 1–19. https://doi.org/10.1080/14680629.2022.2150274

Xi, Z., & Liu, B. (2024). Environmental Effect of Water-Permeable Pavement Materials in Sponge Cities. 464–476. https://doi.org/10.1007/978-981-97-1514-5_47

Zhang, R., Tang, N., Zhu, H., Zeng, J., Bi, Y., & Xi, Y. (2022). Environmental and economic comparison of semi-rigid and flexible base asphalt pavement during construction period. *Journal of Cleaner Production*, *340*, 130791–130791. https://doi.org/10.1016/j.jclepro.2022.130791

Zhang, Z., Sha, A., Liu, X., Bo, L., Gao, J., Jiang, W., & Ma, F. (2020). State-of-the-art of porous asphalt pavement: Experience and considerations of mixture design. *Construction and Building Materials*, *262*, 119998. https://doi.org/10.1016/J.CONBUILDMAT.2020.119998