

Artificial intelligence applications in porous asphalt pavement

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Article Info

Article history:

Received Jan 9, 2026

Revised Aug 26, 2026

Accepted Sep 4, 2026

Keywords:

Artificial intelligence

Hydraulic

Pavement

Permeable

Porous asphalt

ABSTRACT

Porous asphalt pavement (PAP) was developed as a sustainable pavement solution to improve rainwater infiltration, reduce inundation, and improve driving safety. The performance of PAP is influenced by the complex interactions between pore structures, clogging mechanisms, and structural and thermal responses, thus encouraging the application of artificial intelligence (AI) in its modeling. This study aims to comprehensively synthesize the application of AI in PAP through the systematic literature review (SLR) approach. The SLR process was carried out against the publication of the 2021–2026 period from the Elsevier, SpringerLink, and MDPI databases, which resulted in 10 high-quality articles for analysis. The results show that AI enables accurate and non-destructive prediction of hydraulic and clogging performance, while AI-integrated mechanistic models achieve a correlation coefficient of up to 0.994 for structural response and an error below 5% for thermal conductivity. Image-based deep learning and generative models further demonstrate potential for pavement condition assessment and porous microstructure modeling. The novelty of this review lies in integrating evidence on AI applications across the hydraulic, clogging, structural, thermal, and microstructural domains of PAP. The findings highlight the need for an integrated, material-specific AI framework to support sustainable PAP design, monitoring, and maintenance.

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1. INTRODUCTION

Porous asphalt pavement (PAP), or permeable asphalt concrete, has been invented as an eco-friendly pavement material with the capacity to absorb rainwater to counter the effects of flooding as well as to ensure the safety of road users when driving during rainy weather. The open gradation structure of the PAP allows water to flow through the cavities between the aggregates, so that the runoff load on conventional drainage systems can be significantly reduced [1]–[4]. The success of such functions depends largely on the characteristics of the pore structure, especially the percentage of air cavities, the size of the pores, and the connectivity of the pores. A number of studies have shown that water void content is a key parameter that controls the hydraulic performance of PAP. Jomblat *et al.* [1] and Caló *et al.* [2] report that increased air cavities increase the permeability coefficient, but changes in pore size distribution can lead to significant performance variations. Ahmad *et al.* [3] and Xiu *et al.* [4] assert that aggregate gradation and fine aggregate proportions play an important role in balancing between permeability and mechanical stability.

In addition to the initial characteristics of the mixture, clogging is a major problem that limits the long-term performance of PAP [5]–[8]. Nan *et al.* [9] explains that water-borne graded sediment particles are the main cause of blockages in permeable asphalt concrete, with dominant accumulation in the surface layer decreasing porosity and infiltration capacity. A literature study by Zhao *et al.* [10] highlights that multi-scale pore characteristics, including effective porosity, tortuosity, and pore throats, play a critical role in controlling fluid transport and the hydraulic performance of porous materials. This clogging mechanism is influenced by the size and type of clogging particles, traffic conditions, and the pore structure of the mixture [11]. To understand the mechanical behavior of PAP, mechanistic modeling approaches have been widely used. The finite element method (FEM) is applied to evaluate the response of stress, strain, and deflection due to variations in layer thickness, base soil conditions, and traffic loads [12]. Gao *et al.* [13] suggests that increased air cavities can have a cooling effect on pavement surfaces, but potentially affect structural resistance. Lokesh *et al.* [14] combines FEM with a data-driven approach to predict PAP structural response, showing that the relationship between mixed design and structural performance is nonlinear and complex.

The complexity of the relationship between aggregate gradation, air cavity, permeability, clogging, and structural response is driving the use of artificial intelligence (AI) in porous asphalt research. Artificial neural network (ANN) has been used to predict water void content and permeability based on mixed design parameters, with higher accuracy than conventional regression methods [15]–[18]. ANN and optimization-based hybrid models are able to effectively capture the nonlinear relationships between design variables and asphalt pavement performance [19]–[21]. The application of AI is also beginning to be expanded to model the degradation of permeability due to clogging [22]–[24]. These studies show that ANN can be used to predict a decrease in permeability coefficient based on the type of blocker material, clogging cycle, and mixing characteristics [25]–[27]. However, most studies still focus on one performance domain, both hydraulic and structural, without integrating the two in a single analytical framework. Recent developments show the use of image-based deep learning for non-destructive evaluation [28]. Research by Xiao *et al.* [29] using 3D laser imaging combined with convolutional neural networks (CNN) to evaluate clogging levels and permeability performance based on surface texture. A similar approach in the analysis of texture and surface imagery of pavement was also reported by Chen *et al.* [30] and Dong *et al.* [31], which demonstrate the great potential of image-based methods in monitoring pavement conditions. Nonetheless, this approach is still limited to surface evaluation and has not been directly associated with mixed design or structural response.

Based on the review of the literature, it can be concluded that research related to PAP has developed rapidly, especially in the aspects of mixed design, permeability, clogging, structural modeling, and the application of AI. However, these studies are still separate and fragmented. To date, there has been no systematic study that synthesizes the application of AI in all domains of PAP performance, including hydraulic aspects, degradation due to clogging, structural response, and image-based evaluation. Therefore, a systematic literature review (SLR) is needed to comprehensively examine the developments, limitations, and opportunities of AI research in PAP.

Although previous studies have demonstrated the potential of AI for predicting individual aspects of PAP, including permeability, clogging, structural response, thermal properties, and surface characteristics, the available knowledge remains fragmented across separate performance domains. Existing studies generally focus on individual AI applications or specific modelling tasks, while a comprehensive synthesis of AI applications across the hydraulic, clogging, structural, thermal, and image-based domains of PAP is still lacking. Therefore, this study addresses this gap through a SLR that systematically maps current AI approaches, identifies their capabilities and limitations, and highlights opportunities for developing an integrated and material-specific AI framework for PAP.

2. METHOD

2.1. Identification

This study uses the SLR approach to critically synthesize existing studies related to the application of AI in the performance modeling of PAP. The SLR process is carried out with reference to guidelines and best practices in the implementation of systematic reviews in the field of engineering and infrastructure [24], [32], [33]. The three key steps involved in the process of SLR are identification, screening, and inclusion, as illustrated in Figure 1. The justification for choosing this method is summarized as follows:

- a. Scientific justification: to systematically map and synthesize the dispersed knowledge base about the application of AI to PAP, whereas existing studies are confined to different application sectors.
- b. Specific purpose: to offer evidence-based insights to researches/practitioners regarding commonly adopted AI methods, parameters that influence PAP performance, as well as the research gaps that remain opened to decide planning, monitoring, and maintenance activities for PAP.

2.2. Screening

The literature search in this study was carried out systematically on several major scientific databases, namely Elsevier, SpringerLink, and MDPI, with a publication year range of 2021–2026, to cover the initial to current developments of research related to PAP. The search strategy used a combination of keywords that represent the object and the research approach, including "porous asphalt", "permeable asphalt", "clogging", "structural response", as well as "artificial intelligence", "machine learning", "artificial neural network", and "deep learning". All data analyzed came from published journal articles and proceedings, without involving primary data or laboratory experiments. The screening process is conducted through headline and abstract screening, followed by a full-text review, to ensure that the selected articles explicitly address PAP and apply AI-based approaches in modeling hydraulic performance, degradation due to clogging, structural response, or surface characteristics. Articles that are irrelevant, focus on non-porous pavement, or use empirical methods without an AI component are excluded from the study. Table 1 displays the selection criteria. Various databases are selected to guarantee the review's thoroughness in order to capture studies that are both engineering-focused and multidisciplinary by ensuring a minimalist publication bias to cover a wide range of relevant studies [34], [35].

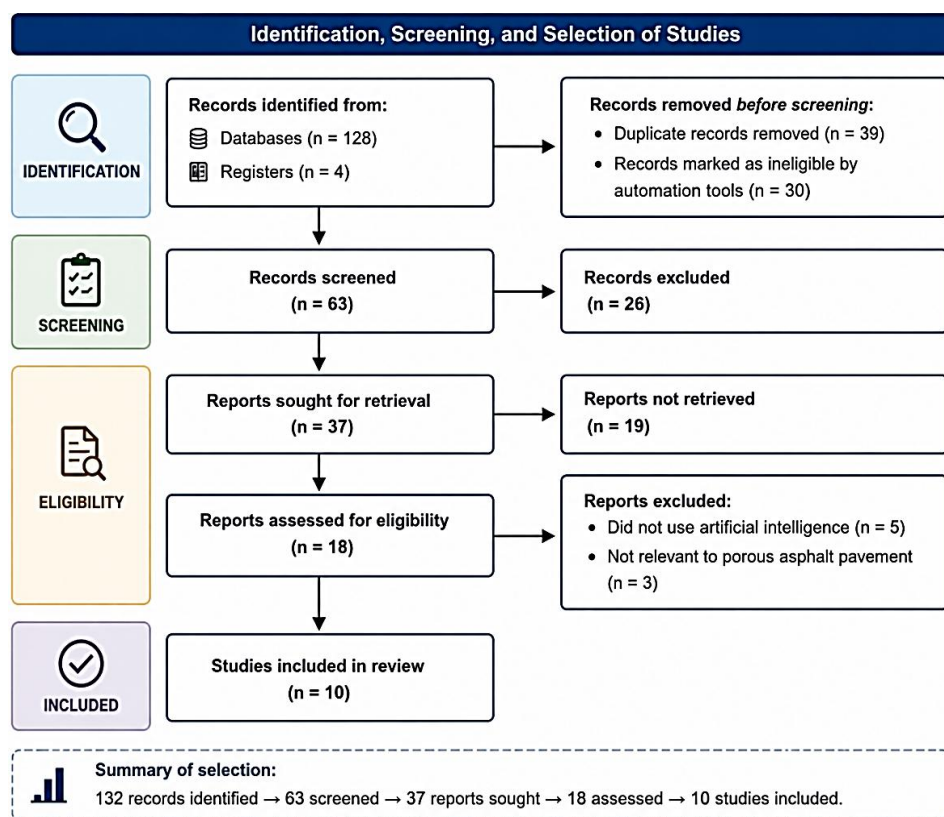


Figure 1. SLR process

Table 1. Selection criteria for articles

No.	Description	Inclusion	Exclusion
1	Subject	PAP and apply AI	Articles that did not discuss PAP or did not use AI approaches were excluded.
2	Published in a journal	Leading Publisher: SpringerLink, MDPI, and Elsevier	Journal and conference articles published by sources other than the leading publisher.
3	Date of publication	2021-2026	Prior to 2021.
4	Type of publication	Journal and conference paper	Book chapters, research document, and dissertations
5	Language	English	Non-English.

2.3. Included

Studies that satisfied the predetermined criteria were examined by the researcher for additional evaluation, in accordance with the review's inclusion standards, after eliminating duplicate records at this point. Subsequently, each study's relevancy was evaluated using its abstract and title. The extracted data were

then assessed for completeness and applicability through an evaluation of quality process. In order to evaluate the thoroughness of the literature examined, the reviewer set criteria based on five areas which included: (A) topic relevance, (B) objectives of the research are clear, (C) use of primary data, (D) analytic techniques, and (E) model framework. The reviewers used a binary scoring system for each of the five criteria. A zero was given where a given criterion was not met, and a one where it was met. This means a reviewer could score an article between zero and five. This methodology has been used for article selection for further analysis [36], see Table 2 and is in alignment with the quality review framework in order to promote consistency and reduce subjective bias in systematic reviews [37].

Table 2. Evaluation of article quality

No.	Sources	A	B	C	D	E	Total score	Explanation
1	Researcher 1 (2021)	1	1	1	1	1	5	Highly qualified
2	Researcher 2 (2022)	1	1	1	1	0	4	Qualified
3	Researcher 3 (2023)	1	1	1	0	0	3	Moderately qualified
4	Researcher 4 (2024)	1	1	0	0	0	2	Not qualified
5	Researcher 5 (2025)	1	0	0	0	0	1	Highly not qualified

2.4. Research questions

The framework for methodology was developed to respond to the following:

- What extent is the use of AI applied in rating the level of hydraulic properties decay due to clogged-induced degraded PAP?
- What extent has AI been applied in evaluating the degradation of hydraulic characteristics in clogged-induced degraded PAP?
- What is the comparison between Traditional mechanistic methods and AI in prediction of stress, strain and deformation of PAP?
- Has any AI methods rationally integrated the hydraulic and structural analyses of PAP?
- What ways are the image-based and deep learning techniques applied in analyzing the pavement's porosity and the design mixtures and structural response of asphalt pavement?

3. RESULTS AND DISCUSSION

3.1. Examine the currently published

10 articles (55.5%) out of 18 that made it through the quality screening stage satisfied the requirements and were utilized in the evidence synthesis procedure. The appropriateness of both the abstract and full text of the selected articles was evaluated and is summarized in Table 3. The research examined 10 articles in total. Figure 2 illustrates the distribution of the selected articles according to their publication year. As shown in the figure, 2024 has the record for the highest number of articles published in a year, contributing 5 (50%) of the articles reviewed. The next articles came from 2025 with 2 articles (20%), 2021 with 2 articles (20%), and finally 2026 with 1 article (10%). In all of the selected studies, the authors identified the same type of research. This designation was empirical research, which entails substantial components of field experiments, field assessments, numerical computation, and data-driven modeling. Peer-reviewed journals published the majority of the articles (80%, 8 articles) and the rest 2 articles (20%) were published in conference proceedings. Looking at the publishers, the most prolific publisher was Elsevier with 5 articles (50%). This was followed by SpringerLink with 4 articles (40%), and MDPI with 1 article (10%). The literature examined consisted primarily of empirical research studies published by international publishing houses, enhancing the credibility and pertinence of the findings collated in this review.

Table 3. Summary of the evaluation results

No.	Sources	Year	Research type	Publication type	Publisher
1	[38]	2026	Empirical	Journal	Elsevier
2	[29]	2025	Empirical	Journal	MDPI
3	[39]	2025	Empirical	Conferences	SpringerLink
4	[40]	2024	Empirical	Journal	Elsevier
5	[41]	2024	Empirical	Journal	SpringerLink
6	[14]	2024	Empirical	Journal	SpringerLink
7	[42]	2024	Empirical	Journal	Elsevier
8	[43]	2024	Empirical	Journal	Elsevier
9	[25]	2021	Empirical	Conferences	SpringerLink
10	[22]	2021	Empirical	Journal	Elsevier

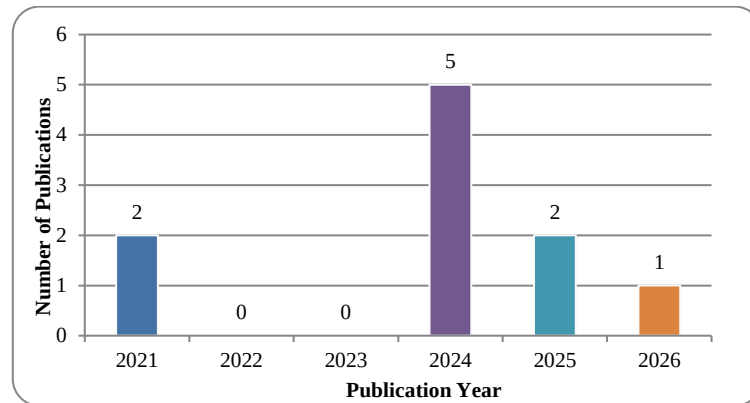


Figure 2. Trends in research

3.2. Assessment of quality results

In this study, quality assessment was conducted on 10 articles that were selected based on inclusion criteria for the synthesis process. Each article was measured on five assessment indicators (A–E) as seen in Table 4. Eight articles received the highest rating (5) and were categorized as very feasible. This indicates that there was high correlation on topic, clarification of the study's goals, primary data utilization, appropriateness of analysis technique, and structurally organized model. On the other hand, 2 articles received a score of 4 and were categorized as feasible mostly because of the lesser degree on the completeness or sophistication of the model structure.

Table 4. Assessment of quality results

No.	Sources	A	B	C	D	E	Total score	Description
1	[38]	1	1	1	1	1	5	Highly qualified
2	[29]	1	1	1	1	1	5	Highly qualified
3	[39]	1	1	1	1	1	5	Highly qualified
4	[40]	1	1	1	1	1	5	Highly qualified
5	[41]	1	1	1	1	1	5	Highly qualified
6	[14]	1	1	1	1	0	4	Qualified
7	[42]	1	1	1	1	1	5	Highly qualified
8	[43]	1	1	1	1	1	5	Highly qualified
9	[25]	1	1	1	1	0	4	Qualified
10	[22]	1	1	1	1	1	5	Highly qualified

As summarized in Table 5, 80% of the selected articles were classified as highly qualified, while the remaining 20% were classified as qualified. These results indicate that the literature included in the review generally demonstrates a high level of methodological quality. Moreover, none of the assessed articles were classified in the lowest quality categories, further supporting the appropriateness of the selected evidence for the synthesis. Therefore, the findings of this study can be considered reliable and credible within the scope of the reviewed literature.

Table 5. Summary of the quality assessment results

Article quality	Highly not qualified (1)	Not qualified (2)	Moderately qualified (3)	Qualified (4)	Highly qualified (5)	Total
Number of articles	0	0	0	2	8	10
Percentages (%)	0	0	0	20	80	100

3.3. Data analysis

Analysis of the ten articles in Table 6 shows that the application of AI in PAP has grown rapidly and covers various performance domains, including hydraulics, clogging, structural, thermal, and microstructural modeling. ANN and image-based deep learning models, such as CNN and ResNet, have been shown to be able to predict permeability and clogging rates in a non-destructive manner with high accuracy, generally above 90%. As illustrated in Figure 3, ANN-based models represent the most frequently adopted approach, followed by CNN/ResNet-based deep learning models, while hybrid and generative models such as ANN–FEM, FE–NN, and CCGAN remain relatively limited but demonstrate strong potential for advanced

performance analysis. The integration of AI with mechanistic methods, such as the FEM, results in a very strong correlation between predicted results and actual data, while also revealing the influence of void characteristics on structural response and pavement fatigue life. In the thermal aspect, the finite element–neural network (FE–NN) approach based on 3D structures is able to predict the thermal conductivity of porous asphalt concrete with an error of less than 5%, showing the advantages of the AI–FEM method compared to conventional approaches. In addition, generative models such as Continuous Conditional GAN (CCGAN) allow the generation of porous asphalt 3D microstructures with controlled porosity from limited micro-CT data, which is consistent with the statistical characteristics of field data. Overall, these findings confirm the important role of AI in multi-domain modeling and comprehensive performance evaluation of PAP.

Table 6. Research on AI applications in PAP

No.	Source	Year	Models used	Results
1	[40]	2024	ANN+RSM	ANN successfully predicted water voids and PAM permeability with high accuracy, close to the results of the experiment compared to RSM.
2	[41]	2024	ANN	ANN achieved 97% prediction accuracy in determining the level of clogging.
3	[14]	2024	ANN+FEM	ANN achieved a correlation coefficient of 0.994 (very high) and the increase in void increased tensile strain as well as decreased pavement fatigue life.
4	[29]	2025	Deep learning (ResNet)+3D Laser	The ResNet-based deep learning model is able to predict the porous permeability of asphalt in a non-destructive manner with an accuracy of over 90%.
5	[25]	2021	Linear regression, ANN, dan CNN	The surface image properties are effective in predicting clogging and surface infiltration rates, with ANN and CNN superior to linear regression.
6	[22]	2021	CNN (ResNet-10, ResNet-12, ResNet-14, ResNet-16, and ResNet-18)	The ResNet-12 model achieved an accuracy of 86% and an F1-score of 89.7%, proving the effectiveness of image-based deep learning for the classification of non-destructive clogging.
7	[42]	2024	X-ray CT+3D reconstruction, 3D particle flow code (PFC3D), and GA-BP ANN	The GA-BP ANN model validates such sensitivity with a prediction error of <5%, confirming the importance of aggregate morphological design to clogging permeability and resistance.
8	[38]	2026	Deep residual fully connected network (DRFCN)	DRFCN's deep learning model based on acoustic features (especially RMS) is able to classify PAC clogging rates with an accuracy of up to 0.96 non-destructively.
9	[43]	2024	FE–NN	The ANN-based FE–NN model is able to predict the thermal conductivity of the PAC of a 3D structure with an error of <5%, showing the advantages of the AI–FEM approach over conventional methods.
10	[39]	2025	Continuous conditional GAN (CCGAN)+latent space interpolation	CCGAN can generate 3D microstructure of porous structure with controlled porosity from limited micro-CT data, with results consistent to statistical properties with field data.

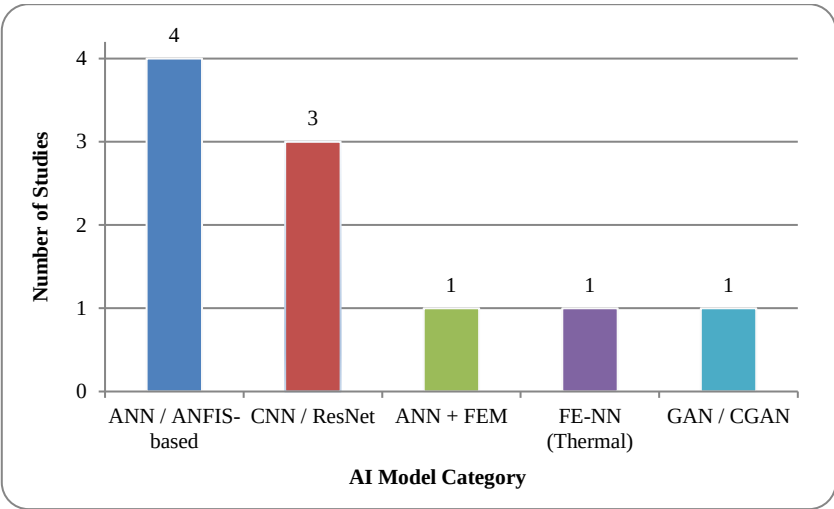


Figure 3. Distribution of AI models used in PAP

Based on the feature importance analysis shown in Figure 4, the pore parameter is the most dominant factor in the performance modeling of PAP based on AI. The water void content and pore size and connectivity have the highest level of importance because they have a direct effect on the permeability, clogging rate, and structural and thermal response of the pavement. Their dominance indicates that the pore structure represents a fundamental link between the physical characteristics of PAP and its functional performance. Therefore, incorporating pore-related variables as key input features enables AI models to capture complex and nonlinear relationships that may not be adequately represented by conventional empirical approaches. The surface texture features and aggregate morphology also show a high level of importance, particularly in image-based approaches and AI-FEM hybrid models for non-destructive evaluation. Meanwhile, the distribution of three-dimensional void microstructures and aggregate thermal conductivity have a medium level of importance, but remain important in advanced modeling based on 3D structures and thermal analysis. Overall, the feature importance results highlight the need to integrate multi-scale pore characteristics into AI models to improve the accuracy, interpretability, and physical relevance of PAP performance prediction.

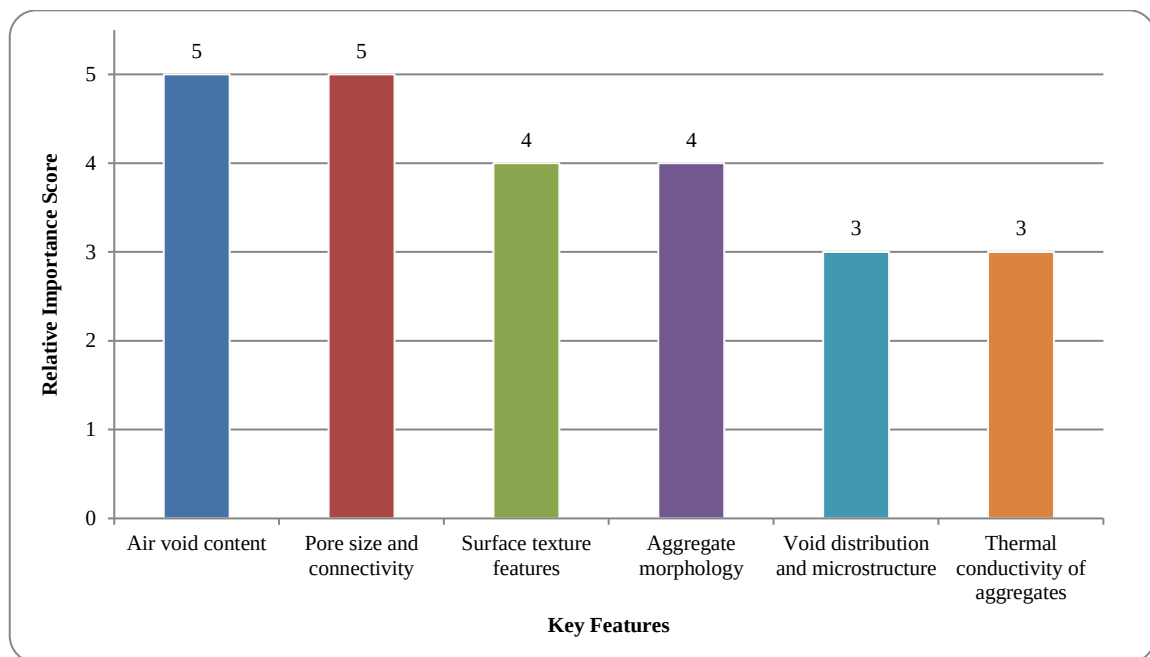


Figure 4. Feature importance in AI models used in PAP

3.4. Discussion

The results of this study show that the application of AI on PAP has fundamentally different characteristics compared to previous studies that were generally carried out on solid asphalt pavement, porous concrete, or non-asphalt porous media [44]–[47]. Previous studies have tended to develop AI models without considering the open aggregate structure, high pore connectivity, and viscoelastic behavior of porous asphalt binders, so they have not fully represented the hydraulic, structural, and thermal mechanisms typical of porous asphalt [48]–[50]. The synthesis of results in this study confirms that pore parameters, specifically water void content, size, and pore connectivity, play a dominant role in controlling permeability, clogging rate, structural response, and thermal conductivity. ANN-based AI and deep learning (CNN/ResNet) approaches have proven to be effective for non-destructive evaluation based on surface imagery, which is relevant because clogging on porous asphalt is generally concentrated in the surface layer. In addition, the integration of AI with mechanistic methods (FEM) as well as the use of generative models such as continuous conditional GAN (CCGAN) expands predictive approaches towards modeling and exploration of material designs. Overall, compared to previous studies that were fragmented and non-specific materials, this study confirms the need for the development of an integrated, material-specific AI framework to support the sustainable design, evaluation of performance, and maintenance of PAP.

4. CONCLUSION

ANN and image-based deep learning models have been proven to be able to predict permeability and clogging rates in a non-destructive manner with high accuracy, generally above 90%, while the integration of AI with the FEM shows excellent ability to model structural responses with a correlation coefficient of up to 0.994. In addition, the three-dimensional structure-based FE–NN approach is able to predict the thermal performance of PAP with an error rate of less than 5%. However, it is still fragmented and has not integrated all PAP performance domains into a single analytical framework. In addition, the integrated and material-specific AI model development is urgently needed to be capable of supporting the sustainable design, monitoring, and maintenance of PAP. This study is subject to several limitations. The review was limited to publications from 2021–2026 and to studies retrieved from the Elsevier, SpringerLink, and MDPI databases; therefore, relevant studies indexed in other databases may not have been included. In addition, the relatively small number of eligible articles reflects the emerging nature of AI applications specifically developed for PAP and limits broader quantitative generalization. Future research should expand the database coverage and develop larger, standardized datasets that integrate hydraulic, clogging, structural, thermal, and image-based information. Further studies should also focus on validating integrated AI models using long-term field data to support more reliable design, monitoring, and maintenance of PAP.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support provided by Universitas Pendidikan Nasional for this research. This research was not supported by any research grant or research contract.

FUNDING INFORMATION

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Darpan Rokade	✓			✓	✓	✓				✓			✓	

C : **C**onceptualization

M : **M**ethodology

So : **S**oftware

Va : **V**alidation

Fo : **F**ormal analysis

I : **I**nterpretation

R : **R**esources

D : **D**ata Curation

O : **O**riginal Draft

E : **E**diting

Vi : **V**isualization

Su : **S**upervision

P : **P**roject administration

Fu : **F**unding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest associated with this research and the publication of this article.

DATA AVAILABILITY

The accompanying author provides the data supporting this study's conclusion.

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