A Review of the Applications of Machine Learning in Asphalt Pavement Engineering

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ABSTRACT

Incorporation of deficient design and construction methods in pavement industry exacerbated with unoptimized maintenance plans has led to unprecedented economic and social costs. Therefore, novel technologies and up-to-date science are most sought for today to respond to the challenges at hand. Artificial Intelligence (AI), one of such new technologies, is currently used to develop machines and algorithms that mimic human's brain. Compared to traditional solutions, AI has proven to be cost- and time-effective in enhancing asphalt pavement design, material production, construction, and maintenance management. The present article delves into the applications of Machine Learning (ML), a subset of AI, in pavement engineering through conducting a review on 150 related scientific articles. According to the results, ML has been employed in 7 various research areas of pavement engineering: Design optimization (11% of the studies), asphalt performance prediction (8%), prediction of asphalt mixture characteristics (33%), detection of surface defects (19%), classification of surface defects (2%), prediction of pavement functional indices (21%), and maintenance plans optimization (6%). Also, aiming to outline the trends in the literature and to represent research gaps and achievements, statistical analysis was presented on: the frequency of published articles in each year, algorithms used for model development, and input features used for predicting the performance of asphalt mixture or pavement sections. It is concluded that ML is an indispensable and necessary tool for improving, optimizing, and conducting the critical processes in pavement design, material production, construction, and management. As a consequence, it is necessary that the applications of ML in pavement engineering be further explored through research. This allows for development of edge-of-science technlogies such as Digital Twins (DTs) in the industry.

KEYWORDS

Asphalt pavement, Artificial Intelligence, Machine Learning, Artificial Neural Network, Optimization

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1. Introduction

Pavements are built to provide a smooth and level surface for driving and also to transfer traffic loads to the subgrade. Accurate engineering design is just as paramount as the right measures and practices for construction of pavement. Subsequently, maintaining the asset in appropriate condition with high serviceability is a vital task. With the ongoing development of road networks, there has been a rise in the demand of high-quality asphalt pavements. To overcome the economic and temporal challenges, it is essential to integrate conventional methods with cutting-edge technologies. Since the beginning of the 21st century, AI solutions have been incorporated in pavement industry to make traditional processes more affordable and time-efficient [1].

Several review articles have already been published in this field, surveying ML algorithms adopted for pavement condition evaluation [2], automated distress detection [3], and pavement performance prediction [4, 5]. However, all the above-mentioned studies are concentrated on the application of ML in pavement maintenance phase, leaving out material production and construction life-cycle stages. There are also other review articles comprehensively investigating the application of ML in pavement engineering life cycle [6, 7], however, the reviewed models were limited to Artificial Neural Networks (ANNs).

The present study looks into pavement engineering literature and thoroughly investigates the ML models developed for materials selection and production, materials characteristics prediction, analyzing materials effects on test results, optimization of pavement maintenance and rehabilitation, and automated defect detection.

2. AI and its subsets

AI is turning into the most prominent tool for resolving the issues in industry and academia [8]. ML is a subset of AI which empowers machines to gain knowledge from its own experience and improve. The principal branch of ML is Deep Learning (DL), composed of Convolutional Neural Networks (CNNs) and more hidden layers than ML algorithms. DL has effectively been used for speech / speaker recognition, object detection, and Natural Language Processing (NLP). Some well-known DL models include Recurrent Neural Networks (RNNs), Generative Adversarial Networks (GANs), and Transformers [9]. AI and its subcategories have been demonstrated in Figure 1 along with exemplary models.

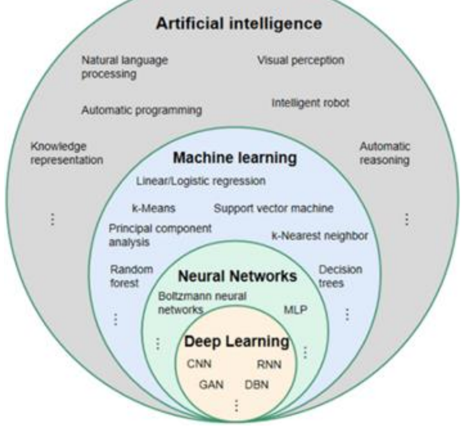

Figure 1. AI and its subcategories [10]

3. Applications of AI in pavement engineering

The latest models developed for the prediction of pavement performance indicators have been reviewed in Table 1. It is observed that various models have been used for prediction International Roughness Index (IRI) and Pavement Condition Index (PCI), namely ANN, Random Forest (RF), Support Vector Machine (SVM), Physics-Guided Neural Networks (PG-NN), Gradient Boosting (GB), Light Gradient Boosting Machine (L-GBM), Extreme Gradient Boosting (XGB), K Nearest Neighbor (KNN), and Linear Regression (LR) [11 - 15]. RF has proven to be one of the strongest ML models in predicting IRI and PCI when supplied with enough data and predictor variables, achieving higher than 90% accuracy. Also, the used datasets included Long-Term Pavement Performance (LTPP) and private datasets obtained from data collection using surveyor vehicles.

Using Physics-informed ML has been one of the novel research trends observed in the literature. These models introduce physics rules into the purely data-driven models and thereby resolve shortcomings such as common-sense reasoning, adherence to physical constraints, and limitation in extrapolation beyond training data [16]. PG-NN was trained on LTPP data in order to predict IRI based on a diverse set of input features including climate, traffic, structure, condition, material, and maintenance data [13]. The model reached an 88.39% accuracy, outperforming the traditional ANN model.

Another research trend spotted in the reviewed articles concerned the “black box nature” of ML models. Explainable AI techniques including calculation of SHAP (SHapely Additive exPlanations) values were implemented to grasp the decision-making process of the model and to recognize the features attended to, in each layer of the model.

Table 1 – Comparison of the latest models developed for predicting pavement performance indicators using AI algorithms

Ref.	Dataset and data volume	ML model	Indicator		Predictor variables						Data splitting share	Model Accuracy
			IRI	PCI	Traffic	Climate	Structure	Material	Condition	Maintenance		
[11]	Data collection at Nablus, Palestine (384 rows)	ANN	-	✓	-	-	-	-	✓	-	70% / 15% / 15%	99.75%
[12]	LTPP (2,708)	RF	✓	-	✓	✓	✓	-	✓	✓	80% / 20%	96%
		SVM										92%
[13]	LTPP (1,287)	PG-NN	✓	-	✓	✓	✓	✓	✓	✓	85% / 15%	88.39%
		ANN										87.89%
[14]	Data collection at Qom, Iran (4,685 rows)	RF	✓	-	-	-	-	-	✓	-	80% / 20%	21.3%
		L-GBM										14.9%
		LR										6.5%
		KNN										15.2%
		GB										19.6%
[15]	LTPP (1,493)	RF	-	✓	✓	✓	✓	✓	✓	-	80% / 20%	91.2%
		XGB										92.3%

Researchers used SHAP analysis to recognize the features that influenced IRI and PCI the most. It was found out that that roughness and pavement age were the most dominant factors in prediction of PCI [15], while aggregate stripping and crack length were the most important features for estimation of IRI [14].

Other subjects covered in the literature included using ML for optimization of mixture and structural design, prediction of asphalt performance and mixture characteristics, detection and classification of surface distresses, prediction of performance indicators, and optimization of the maintenance scenarios. Application of ML in some research areas was barely investigated, including evaluation of environmental phenomena such as albedo and carbonation which are important research topics in pavement Life Cycle Analysis (LCA) [17]. It was also observed that analysis or prediction of the generated energy from pavements was not carried out using ML.

4. Studies in Persian

The articles published in Persian were analyzed separately to better distinguish the approaches taken by researchers with other publications. The efforts of researchers in this section were limited to prediction of Marshall stability using SVM and RF [18], prediction of rutting index for modified asphalt mixture [19], and optimization of the network maintenance plan relying on Fuzzy inference [20].

5. Conclusion

The advances in AI have allowed for accurate analysis and interpretation of data. Nowadays, ML and DL as the subsets of AI are being used to develop systems which are capable of extracting patterns, making decisions, and predicting results without human interference. The article surveyed the applications of ML in asphalt pavement engineering. It was demonstrated that the algorithms have been incorporated in various domains of the industry including design optimization (11% of the studies), prediction of asphalt performance (8%), prediction of asphalt mixture characteristics (33%), detection of surface distresses (19%), classification of surface distresses (2%), prediction of performance indicators (21%), and maintenance plan optimization (6%).

It should be noted that despite the wide application of AI models, there have also been some challenges in implementing them. Dependence on large datasets, lack of generalizability, and the absence of mathematical relationship as the model's output are some of the faced challenges. In this regard, it is suggested that researchers adopt the following in future studies:

- Explainable AI techniques (e.g., SHAP analysis) to recognize how the input features influence the estimated parameter,
- Feature engineering solutions (e.g., recurrent elimination) which avoid entrance of redundant features in the model and thus, improve the model's accuracy,
- Physics-informed models for which different physical information and information integration methods should be evaluated due to their novelty in the literature.

6. References

[1] T. Xu, F. Zhu, E.K. Wong, Y. Fang, Dual many-to-one-encoder-based transfer learning for cross-dataset human action recognition, Image and Vision Computing, 55(2) (2016) 127–137.

[2] N. Sholevar, A. Golroo, S.R. Esfahani, Machine learning techniques for pavement condition evaluation. Automation in Construction, 136 (2021) 104190.

[3] T.B.J. Coenen, A. Golroo, A review on automated pavement distress detection methods, Cogent Engineering, 4(1) (2017) 1374822.

[4] Y. Xu, Z. Zhang, Review of applications of artificial intelligence algorithms in pavement management. Journal of Transportation Engineering, Part B: Pavements, 148(3) (2022) 03122001.

[5] S. Cano-Ortiz, P. Pascual-Muñoz, D. Castro-Fresno, Machine learning algorithms for monitoring pavement performance. Automation in Construction, 139 (2022) 104309.

[6] M. Abambres, A. Ferreira, Application of ANN in pavement engineering: State-of-Art. Authorea Preprints, (2017).

[7] X. Yang, J. Guan, L. Ding, Z. You, V.C. Lee, M.R.M. Hasan, X. Cheng, Research and applications of artificial neural network in pavement engineering: a state-of-the-art review, Journal of Traffic and Transportation Engineering (English Edition), 8(6) (2021) 1000-1021.

[8] K. Kersting, Machine learning and artificial intelligence: two fellow travelers on the quest for intelligent behavior in machines, Frontiers in big Data, 1 (2018) 6-10.

[9] M.H.M., Noor, A.O. Ige, A survey on state-of-the-art deep learning applications and challenges, Engineering Applications of Artificial Intelligence, 159 (2025) 111225.

[10] B.O. Antwi, B.O. Adelakun, A.O. Eziefule. Transforming financial reporting with AI: Enhancing accuracy and timeliness, International Journal of Advanced Economics, 6(6) (2024) 205-223.

[11] A. Issa, H. Samaneh, M. Ghanim, Predicting pavement condition index using artificial neural networks approach, Ain Shams Engineering Journal, 13(1) (2022) 101490.

[12] M. Ghodratabadi, A. Golroo, M.S. Entezari, Machine learning for predicting pavement roughness and optimising maintenance, *Road* Materials and Pavement Design, (2025) 1-20.

[13] K. Chen, M.E. Torbaghan, N. Thom, A. Faramarzi, Physics-guided neural network for predicting international roughness index on flexible pavements considering accuracy, uncertainty and stability, Engineering Applications of Artificial Intelligence, 142 (2025) 109922.

[14] A. Yazdi, M.H. Dehnad, A Case Study on Predicting Asphalt Pavement Distress Using Advanced Machine Learning Techniques and Road Surface Inspection Data, Case Studies in Construction Materials, (2025) e05291.

[15] M. Shaheen, R.A. Elsayed, H. Ghazoly, W.A. Bekheet, Explainable and economical AI-based approach for PCI assessment, International Journal of Pavement Engineering, 26(1) (2025) 2531195.

[16] Y. Wu, B. Sicard, S.A. Gadsden, Physics-informed machine learning: A comprehensive review on applications in anomaly detection and condition monitoring, Expert Systems with Applications, 255 (2024) 124678.

[17] M.S. Entezari, R. Tanzadeh, F. Moghadas Nejad, Economic, Environmental, and Social Assessment of Concrete Pavement Life Cycle: A Literature Review, Sharif Journal of Civil Engineering, 41(1) (2025) 110-129.

[18] H. Hosseinzadeh, A. Hasani, S. Arman, A.S. Hejazi, Predicting Marshall Asphalt Stability Using Supervised Machine Learning Algorithms, support vector machine and random forest, Journal of Transportation Research, 20(3) (2023) 249-262 (in Persian).

[19] A. Amini, Presenting Predictive Models of Rheological Characteristics of Modified Bitumens

Containing SBS and Carbon Nanotubes Using Nonlinear Regression and Neural Network, Journal of Transportation Research, 22(3) (2025) 373-384 (in Persian).
[20] H. Behbahani, N. Nadimi, M. Khaleghi, Introducing a New Method for the Pavements' Maintenance and Rehabilitation Planning, Amirkabir Journal of Civil Engineering, 53(7) (2021) 2801-2820 (in Persian).