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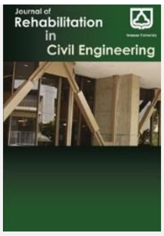

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Research and Comparison of Nano-Asphalt Mixture Fracture Toughness Based on Machine Learning Technique

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ABSTRACT

Low-temperature cracking (LTC) is a critical form of pavement distress in cold regions. The fracture toughness in the semicircular bending (SCB) test serves as an indicator of LTC growth. Firstly, this study evaluated the effect of adding nano Al_2O_3 on the improvement of hot mix asphalt (HMA) fracture toughness. Another goal of the paper was to investigate the influence of different parameters, such as temperature (-5, -15, and -25 °C), loading mode (I, II, and I/II), crack geometry (vertical and angular cracks), and nano-modification, on the fracture toughness of HMA by using machine learning technique. An artificial neural network (ANN) was employed to quantify the impact of these parameters. The findings of this research clearly show that although asphalt mixtures in cold region are prone to thermal cracks, the addition of nano Al_2O_3 improves their resistance by 12% in comparison with control mixtures. The ANN analysis identified loading mode is the most significant factor affecting fracture toughness (48% contribution). Temperature followed with a 28% contribution, while crack geometry and nano Al_2O_3 modification each contributed 12%.

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1. Introduction

Asphalt pavements in cold regions are more susceptible to cracking due to the combined effects of traffic loading and weathering. These distresses not only reduce ride quality but also necessitate frequent maintenance and rehabilitation, consuming a significant portion of infrastructure budgets worldwide [1]. Identifying and mitigating the factors contributing to cracking is crucial for pavement longevity. As previous research has shown, the failure behavior of asphalt concrete is significantly influenced by both temperature and loading rate. At higher temperatures and under slower loading rates, the material exhibits viscoplastic behavior, characterized by the properties of both viscous and plastic materials. Conversely, at lower temperatures and under faster loading rates, asphalt concrete behaves in a brittle manner, similar to a linear elastic material [2]. Although fracture mechanisms, crack propagation, and the influence of various factors on asphalt material fracture have been extensively studied, a key area of research remains the investigation of fracture toughness, particularly at sub-zero temperatures. Enhancing the fracture resistance of asphalt concrete has been a persistent area of research. Numerous studies have explored the modification or incorporation of various materials to achieve this goal [3–6]. In addition, extensive research has investigated the fracture resistance of asphalt mixtures under mode I and mode II loading conditions [7–10]. Given that asphalt concrete is subjected to a combination of tensile loads from thermal stresses and both tensile and shear loads from vehicle wheels, it is highly probable that crack growth will occur under mixed mode I/II loading [11]. However, this area has received relatively little research attention.

In cold regions, low-temperature cracking represents a predominant distress mechanism in asphalt pavements. To mitigate this issue, a thorough understanding of factors influencing crack initiation and propagation is crucial. Additionally, research on methods to predict fracture toughness at low temperatures is essential. Several factors are known to influence the fracture toughness of asphalt mixtures, including loading mode, mixture temperature, and crack geometry [12,13]. This study aimed to quantify the individual and combined effects of these parameters on low-temperature cracking of asphalt mixtures using fracture toughness as the key metric. Machine learning techniques (linear regression and artificial neural network) have been employed to achieve this objective. Furthermore, the investigation explored the influence of incorporating nano Al_2O_3 on the fracture toughness and cracking behavior of asphalt mixtures at low temperatures.

2. Factors affecting the failure of cracked asphalt mixtures

Cracking in asphalt surfaces is primarily caused by two factors: thermal stress and mechanical stress from vehicular traffic. In fracture mechanics, the collective term for the pattern of crack propagation, the method and form of separation, and the resulting geometric fragmentation of the component is fracture mode [14]. Figure 1 illustrates how fracture mechanics categorizes crack behavior based on the loading conditions that induce the crack. Three primary fracture modes exist: Mode I, opening mode, occurs when tensile stresses pull the crack faces apart perpendicular to the crack plane. Mode II, in-plane shear mode, arises when the crack faces slide past each other in a direction parallel to the crack plane. Finally, Mode III, out-of-plane shear mode, occurs when the crack faces slide in a direction perpendicular to both the crack plane and the crack propagation direction.

Thermal loading, along with the contraction and expansion of the asphalt layer, leads to the separation of crack edges. As a result, cracks in the asphalt surface, subjected to daily or seasonal thermal loading, are exposed to pure tensile stresses, resulting in Mode I deformation. However, mechanical loads arising from vehicular traffic have a more intricate impact on the deformation behavior of cracked asphalt layers. These mechanical loads can further induce both shear mode and Mode I loading in the asphalt surface [15].

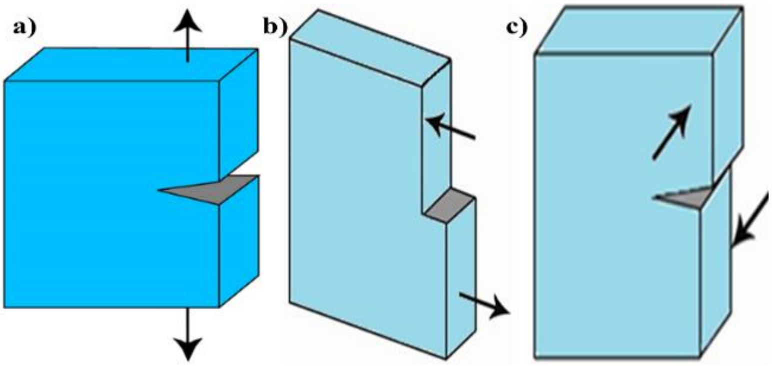

Fig. 1. Loading modes, a) Mode I b) Mode II c) Mode III.

Figure 2 illustrates the distribution of bending and shear stresses at the crack tip, induced by the passage of vehicle wheels. The figure clearly indicates that when a wheel passes directly over the crack, only a tensile load (Mode I) and the resultant bending stress are experienced at the crack location. However, if the wheel is positioned at a certain distance from either side of the crack tip, both bending and shear stresses are generated at the crack tip. This evidence substantiates that the propagation of the crack in the pavement is a combination of Modes I and II.

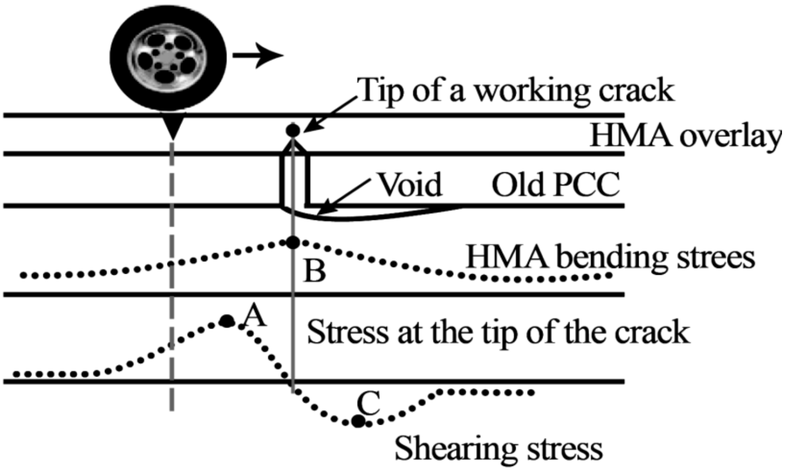

Fig. 2. Stress diagram for the crack tip in an asphalt layer [1].

3. Materials and methods

3.1. Materials

Limestone aggregates were used in this research. The aggregates were obtained from the Makadam plant in Varamin, Tehran Province, and conformed to the middle of the gradation specified in the Iran Asphalt Mixture Standard (code 234), with a maximum nominal size of 19 mm for the Topeka layer. Details of the gradation are presented in Table 1. The gradation test for coarse aggregates adhered to the AASHTO T-27 standard, whereas a washing method was used for fine aggregates. Tests for the bulk specific gravity, apparent specific gravity, and water absorption percentage of the aggregate retained on the No. 8 sieve were conducted according to the AASHTO T-85 standard. The AASHTO T-84 standard guided the testing of aggregates passing the No. 8 sieve and retained on the No. 200 sieve. The results of these tests are summarized in Table 2.

The bitumen used in this study was 60-70 grade bitumen (PG 64-22) sourced from the Pasargad Oil Refinery. Its specifications are provided in Table 3.

Table 1. Gradation of aggregate materials according to code 234 for the Topeka layer.

Sieve size (mm)	Passing Percentage	Maximum	Minimum
19	100	100	100
12.5	93.3	100	90
4.75	46.8	74	44
2.36	34.5	58	28
0.3	10.5	21	5
0.075	4.3	10	2

Table 2. Bulk and apparent specific gravity and water absorption percentage of aggregate materials.

Aggregate	Specific gravity		Water absorption
	bulk	Apparent	
aggregate retained on sieve No. 8	2.638	2.685	0.7
aggregate passed through sieve No. 8, retained on 200	2.619	2.708	1.3
aggregate passed through sieve 200	2.723		-
Specific gravity of actual aggregate mixture (Gsb)	2.635		

Table 3. Specifications of the bitumen used in this research.

Specific Gravity at 25°c (g/cm3)	Penetration grade at 25°C (0.1 mm)	Softening point (°c)	Ductility at 25 °C (cm)	Degree of purity
1.013	68	50	102	99.6

Nano Al_2O_3 is a bitumen additive that enhances the low-temperature crack resistance of bitumen and asphalt mixtures. Shafabakhsh et al. (2017) studied how nano- Al_2O_3 affects the mechanical properties of stone mastic asphalt mixture. They prepared bitumen samples with different nano Al_2O_3 contents (0.3, 0.6, 0.9, and 1.2 wt% of bitumen) and tested their physical and rheological properties. The results showed that the optimal nano Al_2O_3 content for bitumen performance was 0.6 wt%. Asphalt mixture tests also confirmed that adding 0.6 wt% nano Al_2O_3 to bitumen significantly enhanced the durability and crack resistance of the mixtures [16]. Previous studies have also confirmed the positive effects of nano Al_2O_3 on bitumen and asphalt mixture performance [17,18]. In this study, bitumen was modified with 0.6 wt% nano Al_2O_3 and then used to produce asphalt mixtures. The fracture toughness of asphalt samples with and without nano Al_2O_3 was compared. Table 4 shows the properties of nano Al_2O_3 used in this study. Figure 3 presents the SEM-EDX analysis of nano Al_2O_3 modified bitumen, which revealed that carbon was the dominant element, accounting for more than 90% of its composition.

Table 4. Specifications of the nano Al_2O_3 used in this study.

Chemical Formula	Specific Weight (g/cm^3)	Particle Size (nm)	Specific Surface Area (m^2/g)
Nano Al_2O_3	0.9	60	160

This study employed the Marshall method (ASTM D1559) to determine the optimal bitumen content for asphalt mixtures. Optimal bitumen content refers to the bitumen percentage that balances high specific gravity and strength while maintaining a specific target air void content in the asphalt mixture. Asphalt mixture samples with varying pure bitumen percentages were made by applying 75 blows on each side of the sample according to the Marshall method. AASHTO T-166 was used to determine the specific gravity of compacted asphalt samples, while AASHTO T-209 was used to compute their strength and flow properties. The true specific gravity of asphalt, Marshall stability, flow, air voids, percent voids in mineral aggregate (V.M.A), and percent voids filled with bitumen (V.F.A) were computed using the MS-2 Asphalt Institute standard. Based on tests and computations, the optimum bitumen percentage was determined to be 5%. This value was then used to produce SCB asphalt mix samples.

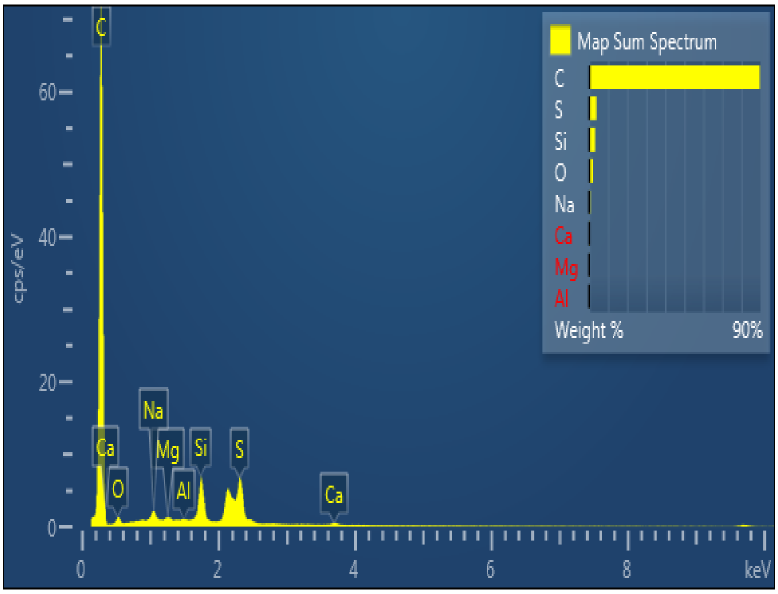

Fig. 3. EDX analysis performed on the bitumen-nano Al_2O_3 compound.3.2. Asphalt mix design.

3.3. SCB test

For the construction of SCB samples, initial cylindrical samples were fabricated with a diameter of 15 cm and a height of 18 cm, adhering to the AASHTO TP-105-13. The aggregates and bitumen were heated in a furnace at 152-156 °C for 16 hours. Subsequently, they were transferred into a container and weighed. Following this, both control and modified bitumen were incorporated into the aggregates at an optimal percentage. At this point, the mixture and bitumen were stirred until a homogeneous mix was achieved. This mixture was then poured into a cylindrical mold and relocated to a gyratory compaction device, where the compaction process was executed at a temperature range of 143-146 °C. Fabrication of SCB samples from cylindrical ones began by slicing the cylindrical samples into disks approximately 1.3 cm thick using a cutting machine with a rotating disc or saw and a water spray. To minimize alterations in the mechanical properties of the asphalt samples, the cutting operation was performed with extreme caution at a slow pace. Concurrently, the cutting site was cooled with a water spray. To generate SCB samples, the sliced samples were then bisected at their center. After the SCB samples were fabricated, cracks were created in them using a water jet machine. The cracks were of two types: vertical and angular. The velocity of the water jet machine and the securement of the samples beneath it were adjusted in order to produce linear cracks in all the samples without any deviations.

The fracture toughness test requires a specific crack length. This ensures that the crack tip location is far enough from the supports, load application point, and sample boundaries. Such distancing is necessary to avoid the influence of stress concentration at the supports on the stress field around the crack tip. Therefore, most fracture mechanics studies target an a/R ratio between 0.3 and 0.5, where 'a' represents the crack length and 'R' represents the characteristic dimension of the sample [19]. The crack length in all the samples was about 22.5 mm, which gives a ratio of a/R of about 0.3 for the SCB samples. Figure 4 illustrates these steps.

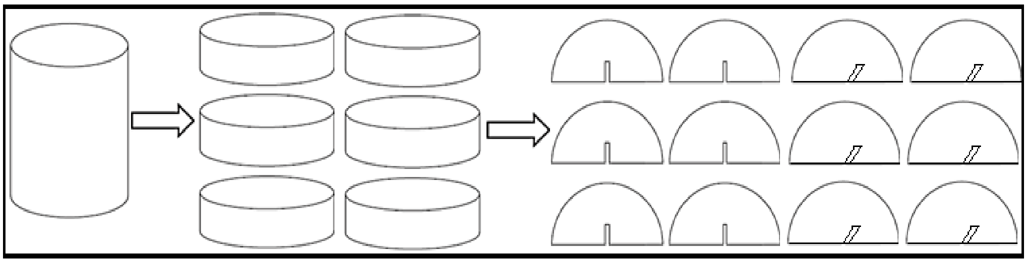

Fig. 4. Steps of preparing SCB samples.

Prepared laboratory specimens for the fracture toughness test are stored in a freezer set to the desired test temperature for 8 hours to ensure uniform temperature throughout. Then, the specimens are sequentially removed, quickly positioned in the pressure test device, and loaded. For each specimen, the distance of the lower supports is predetermined. The samples are then loaded at a constant rate in a three-point bending configuration until the point of fracture and crack propagation. During the test, the load-displacement outcomes for each specimen are documented by the computer. The device software records the load as a function of displacement from the onset of loading until the point of fracture. The fracture toughness value (K) for each sample is derived from Equation 1, where KI and KII pertain to fracture toughness in modes I and II, respectively, and are extracted from Equations 2 and 3.

$$K = \sqrt{K_I^2 + K_{II}^2} \quad (1)$$

$$K_I = (P/2)Rt\sqrt{\pi a}Y_I \quad (2)$$

$$K_{II} = (P/2)Rt\sqrt{\pi a}Y_I \quad (3)$$

In these equations, P is the concentrated load on the specimen, a is the crack length, R is the radius, t is the thickness, and YI and YII are the shape factors of the specimens. The parameter Me, defined by Equation 4, indicates the relative contributions of modes I and II under different loading conditions of mixed mode fracture. Me equals 1 for pure mode I and 0 for pure mode II. Table 5 summarizes the number of specimens and research variables used in this study.

$$Me = (2/\pi)\ tan^{-1}(KI/KII\ ) \quad (4)$$

Table 5. Number of samples and research variables.

Variables	value
Crack Geometry	Vertical and Angular
Temperature (°C)	-5, -15, -25
Me	0, 0.2, 0.4, 0.6, 0.8, 1
Nano Al_2O_3 content (%)	0, 0.6

4. Results of fracture toughness tests

Figures 5 and 6 present the fracture toughness values of asphalt mixtures at varying temperatures, both in the presence and absence of nano Al_2O_3, under different I/II modes, and with two distinct types of cracks: vertical and angular. The results indicate that fracture toughness (Keff) increases as the temperature decreases from -5°C to -15°C and further to -25°C. This suggests that asphalt samples at lower temperatures have a higher modulus of elasticity and increased stiffness, making them more resistant to cracking. The trend is similar for each loading mode, but the values differ. For instance, the results indicate that for angular cracks and the pure tensile loading mode (Me=1), the toughness value at -25°C is about 8% and 25% higher than at -15°C and -5°C, respectively.

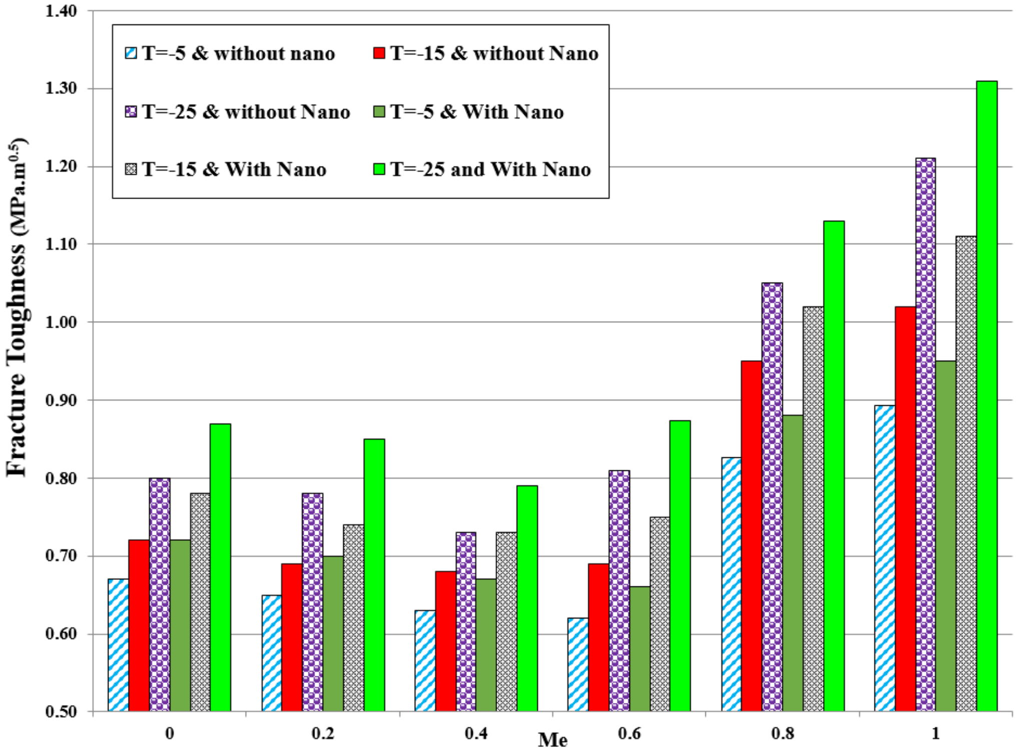

Fig. 5. Fracture toughness values of samples with vertical cracks.

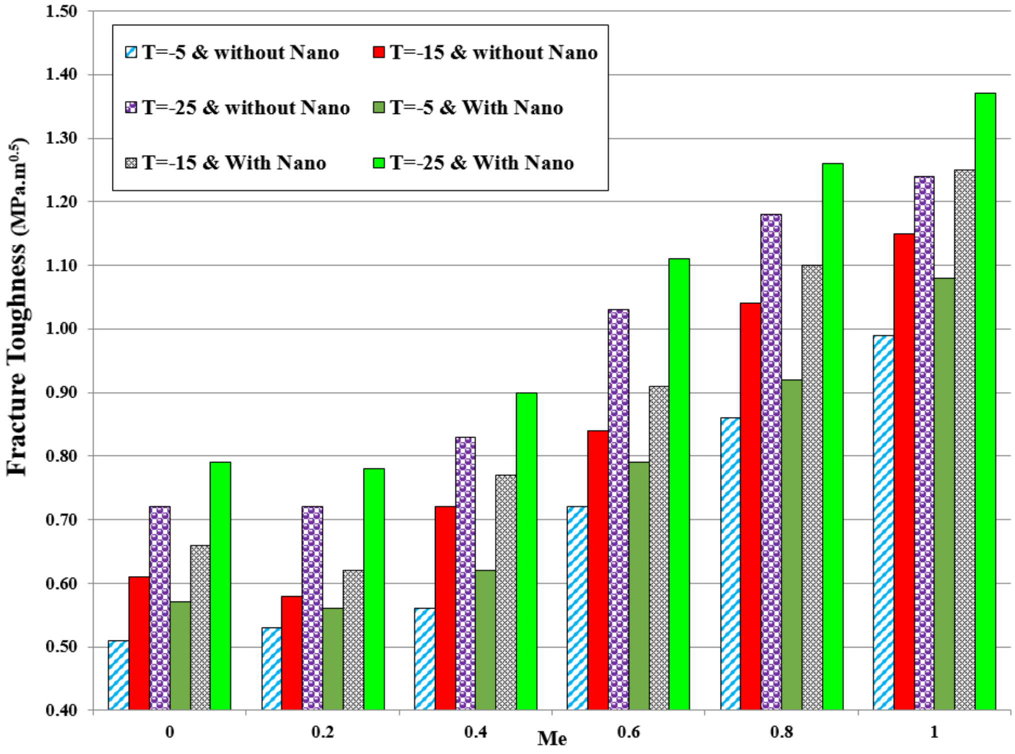

Fig. 6. Fracture toughness values of samples with angular cracks.

A comparative analysis of the results in two geometrical states, namely, vertical and angular cracks, reveals that as the loading mode approaches shear (with Me values of 0.0 and 0.2), samples with vertical cracks exhibit greater resistance compared to those with angular cracks. However, as the Me value increases to 0.4, indicating a shift towards a tensile loading, it is the samples with angular cracks that display superior resistance. This trend persists up to the point of pure tensile loading (where Me equals 1).

This research also investigates the effect of nano Al_2O_3 addition on the fracture toughness of asphalt mix samples. The fracture toughness results reveal that adding 0.6% nano Al_2O_3 enhances the crack resistance of asphalt mix samples. A further analysis of the results indicates that this enhancement occurs uniformly within the range of 6% to 12% and implies that the influence of nano Al_2O_3 on fracture toughness is independent of the loading mode and test temperature, and is consistent across all conditions. The main reason for the effectiveness of nano Al_2O_3 is attributed to the high surface-to-volume ratio of this nanomaterial and the enhancement of the adhesion ability of bitumen, especially at low temperatures.

5. Predictive models of fracture toughness based on machine learning techniques

This section investigates the relationship between fracture toughness (dependent variable) and the influence of nano Al_2O_3 addition, type of cracking, fracture mode, and temperature (independent variables) using experimental data. Due to the presence of multiple independent parameters of both quantitative and qualitative types, two models were employed: Linear Regression (LR) and Artificial Neural Network (ANN).

LR offers a simple and interpretable approach, but struggles with capturing non-linear relationships between variables. ANNs excel at handling complex interactions, but their interpretability can be limited. This study utilizes a fully connected ANN model with five hidden layers (each with 100 neurons) that employs the ReLU (Rectified Linear Unit) activation function for efficient learning. The mean squared error (MSE) loss function measures the difference between predicted and actual values. Adam, an adaptive learning rate optimization algorithm, trains the network with a learning rate of 0.0002. Figure 7 illustrates the ANN architecture with the input layer, five hidden layers, and the output layer. Each layer incorporates bias, a fixed numerical value, alongside the weighted sum of inputs before processing by the activation function. The models' accuracy is assessed by the explained variance and the determination coefficient (R^2). Higher values of these two parameters indicate better modeling performance.

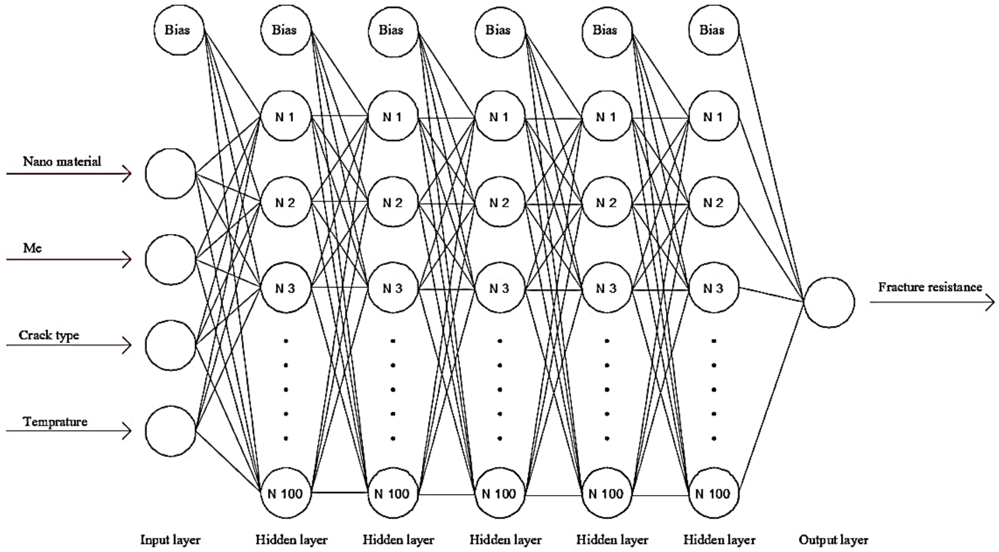

Fig. 7. Architecture of the ANN model in this research.

The linear regression (LR) model's fracture toughness is given by Equations 5 to 8. Equations 5 and 6 show this parameter for samples including nano Al_2O_3 with vertical and angular crack geometries, respectively. Equations 7 and 8 show this parameter for control samples with vertical and angular crack geometries, respectively. The explained variance and R^2 values from Table 6 indicate that the ANN model has an accuracy above 98%, while the LR model has an accuracy of 90%. Therefore, both models can effectively model the relationship between the fracture toughness (dependent parameter) and the percentage of nano Al_2O_3, type of cracking, fracture mode, and temperature (independent parameters). However, the ANN model outperforms the LR model. Figures 8 and 9 display the fracture toughness values, the predictions of the models, and the errors for both the LR and ANN models. Figures 10 and 11 illustrate the correlation between the actual and predicted values of the training and testing data for both models. It is clear from these figures that the ANN model has demonstrated a high degree of accuracy in fitting the experimental data from this study.

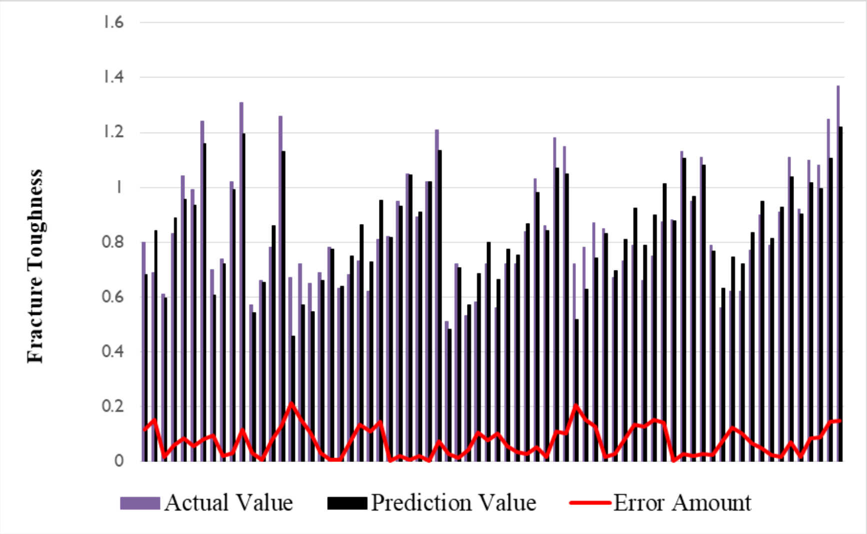

Fig. 8. Actual values of fracture toughness, prediction, and error amounts of the LR model.

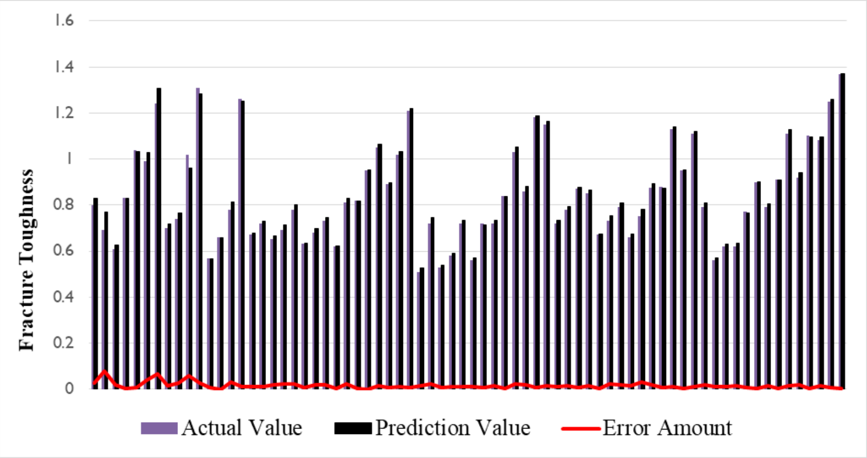

Fig. 9. Actual values of fracture toughness, prediction, and error amounts of ANN model.

$$\text{Fracture resistance} = 0.4589 - 0.01156\,T + 0.4640\,Me \tag{5}$$

$$\text{Fracture resistance} = 0.4850 - 0.01156\,T + 0.4640\,Me \tag{6}$$

$$\text{Fracture resistance} = 0.3939 - 0.01156\,T + 0.4640\,Me \tag{7}$$

$$\text{Fracture resistance} = 0.4199 - 0.01156\,T + 0.4640\,Me \tag{8}$$

Table 6. Values of Explained Variance, R^2, MAE, and MSE.

Model	Explained variance	R^2	Mean absolute error	Mean square error
Linear regression	0.8951	0.8764	0.0708	0.0069
Artificial neural network	0.9827	0.9824	0.0252	0.001

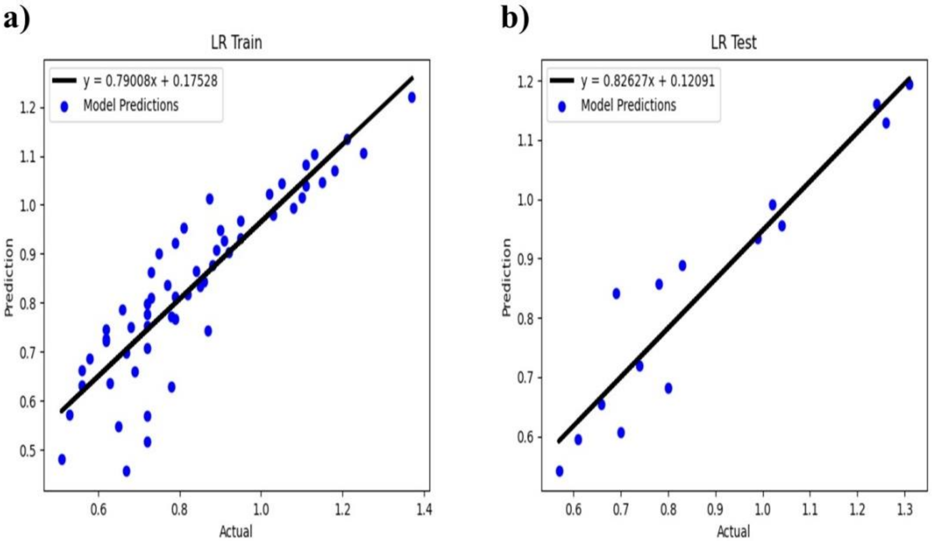

Fig. 10. Relationships between actual values and predictions of the LR model for data: (a) Training (b) Testing.

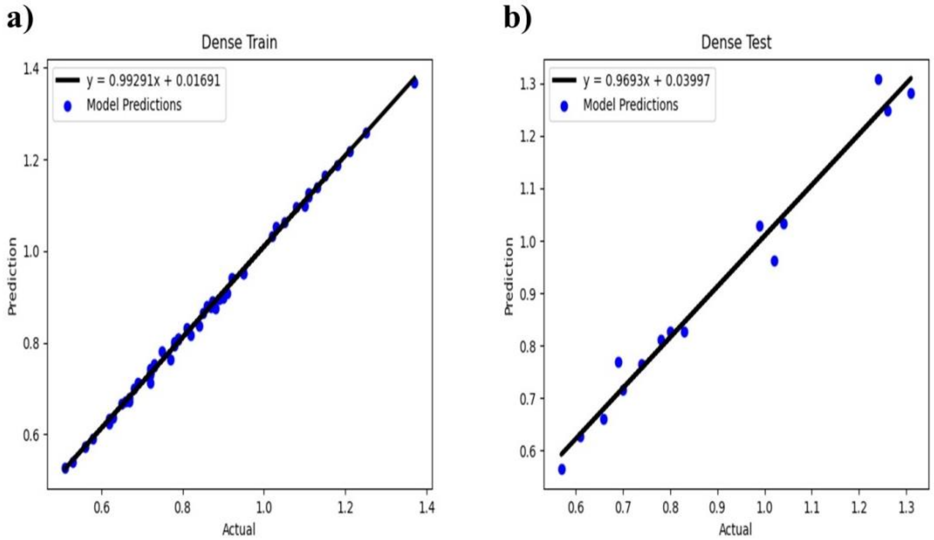

Fig. 11. Relationships between actual values and predictions of the ANN model for data: (a) Training (b) Testing.

This section analyzes only the ANN model results for the sensitivity analysis of parameters influencing fracture toughness, as it outperformed the LR model. Table 7 presents the percentage effect of each parameter on fracture toughness. The mode of fracture, sample temperature, type of cracking, and the addition of nano Al_2O_3 are the most influential factors on fracture toughness, respectively. The fracture mode parameter (Me) has a 48% effect and is the key factor in the cracking of asphalt mixtures. The ANN results show that the temperature parameter has a 28% effect on fracture toughness, highlighting its significance and impact on the cracking of the mixture. These two variables are the primary factors influencing the fracture toughness of asphalt mixtures. Following them, the parameters of crack type (vertical or angular) and the addition of nano Al_2O_3 each have an equal impact of 12%.

Table 7. Impact percentage of independent parameters on fracture toughness.

Addition of Nano Al_2O_3	Crack Type	Me	Temperature
12	12	48	28

6. Conclusion

Fracture toughness is a mechanical characteristic that denotes a material’s resistance to rapid or sudden fracturing in the presence of a crack. Asphalt pavements require sufficient fracture toughness to withstand the stresses encountered across various temperature ranges. Given this importance, studying the factors influencing crack initiation and propagation is crucial. Furthermore, methods for predicting and identifying the fracture properties of asphalt mixtures and their influencing factors, are essential. This research investigates the fracture toughness of nano Al_2O_3 modified asphalt mixtures under a combined tensile-shear mode by examining the crack geometry and loading method on Semi-Circular Bending (SCB) samples. The research objectives are achieved by selecting and analyzing temperatures of -5, -15, and -25 °C, a combined tensile-shear loading mode, and vertical and angular crack geometries. The main findings of this research are:

The fracture toughness increases as the temperature decreases from -5°C to -15°C and then to -25°C for both vertical and angular crack samples. This suggests that the asphalt samples exhibit a lower potential for crack growth at lower temperatures.

- As the loading mode approaches shear (Me = 0 and 0.2), samples with vertical cracks exhibit greater resistance compared to those with angular cracks. Conversely, when the loading mode leans more towards tension, samples with angular cracks demonstrate superior resistance.
- The presence or absence of nano Al_2O_3 affects fracture toughness by approximately 6 to 12 percent. The impact of adding nano Al_2O_3 on the fracture toughness of the asphalt mix is independent of the loading mode, test temperature, and crack type, and is observed across all conditions.
- The research conducted in this study has demonstrated that the ANN model, when used for predicting fracture toughness in asphalt mixtures, exhibits an accuracy exceeding 98%. In contrast, the LR model has achieved an accuracy of 90%. Thus, both the ANN and LR models are suitable for this purpose, although the ANN model has outperformed the regression model.
- An analysis of the ANN model revealed that, among the parameters investigated in this study, the fracture mode parameter exerted the most significant influence on the fracture toughness of asphalt mix, accounting for 48% of the effect. Subsequently, the temperature parameter had a 28% influence. Beyond these two, the parameters of crack type and the addition of nano Al_2O_3 each contributed equally, with an impact of 12%.
- All the results of this study indicate that the fracture toughness of the samples containing nano Al_2O_3 is higher than that of the control samples. This suggests that the use of nano Al_2O_3 in asphalt mixtures can be considered a solution for use in cold climates.

7. Future perspectives

Low-temperature cracking (LTC) constitutes a significant distress mechanism for asphalt pavements in cold regions. The primary objectives of this study were to investigate the effects of different parameters on the fracture resistance of asphalt mixtures at low temperatures using machine

learning methods and to improve it by adding nano Al_2O_3. Future research directions can be as follows:
Evaluation of different aggregate types and sizes, as well as various asphalt binder types, on the low-temperature cracking (LTC) of hot mix asphalt (HMA).

- Life cycle assessment (LCA) before and after the addition of nano Al_2O_3.
- Construction of a test section of asphalt pavement incorporating nano Al_2O_3.

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Conflicts of interest

The author (Gh. Shafabakhsh) is an Editorial Board Member for Journal of Rehabilitation in Civil Engineering and was not involved in the editorial review or the decision to publish this article.

Authors’ contribution statement

Gholamali Shafabakhsh: Project Administration, Supervision, Conceptualization, Methodology.

Mostafa Sadeghnejad: Conceptualization, Visualization, Methodology, Formal analysis, Data Curation, Writing - Review & Editing, Software.

Milad Keneshlou: Writing - Original Draft, Formal analysis, Resources, Experimental Investigation, Software.

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