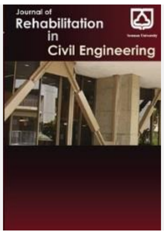

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Comprehensive Assessment of Nano-Silica Modified Asphalt Mixtures: Influence of RAP Content, Aging, and Performance Characteristics

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ABSTRACT

Using recycled asphalt pavement (RAP) in asphalt mixtures is common for improving sustainability, but it can lower performance because of the aging and hardening of RAP binder. Aged RAP is stiffer, less flexible, and more prone to cracking. The performance decreases with the age of RAP. Adding materials like nano-materials can help reduce these issues. This study investigates the combined impact of RAP content, RAP age, and Nano-silica (SiO_2) on asphalt performance, focusing on fracture resistance, fatigue resistance, and moisture susceptibility. Asphalt mixtures with 25%, 50%, and 75% RAP were tested using two types of RAPs with different ages (5 and 10 years). Nano-SiO_2 was added in varying percentages (0%, 1%, 1.5%, and 2%) to evaluate its effects. The performance was assessed using the semi-circular bending test for fracture resistance, the indirect tensile fatigue test for fatigue resistance, and the tensile strength ratio (TSR) test for moisture susceptibility. Results showed that Nano-SiO_2 improved the fracture and fatigue resistance of mixtures, especially those with lower RAP content. At 25% RAP, the addition of 1.5% and 2% Nano-SiO_2 enhanced fracture and fatigue resistance by 15-20%. For mixtures with 50% and 75% RAP, Nano-SiO_2 led to significant improvements, with the best results seen at 2% nano-silica. Nano-SiO_2 also enhanced moisture resistance, increasing TSR values above the 80% threshold. Nano-silica mitigated the effects of aging, particularly in mixtures with higher RAP content. According to this comprehensive evaluation, it is recommended to use 25-50% of RAP using 1.5% of Nano-SiO_2 to achieve high-performance mixtures.

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1. Introduction

Asphalt pavement is one of the most commonly used materials for road construction and maintenance. Due to the constant exposure to environmental factors such as temperature variations, moisture, and heavy traffic loads, asphalt mixtures often face performance-related issues such as cracking, moisture damage, and fatigue [1,2]. These issues can lead to the degradation of the pavement structure, resulting in costly repairs and reduced service life. To address these challenges, the asphalt industry has been exploring methods to enhance the performance and longevity of asphalt mixtures through various modifications. Among these, the use of recycled asphalt pavement (RAP) and innovative [3] additives like nano materials have emerged as promising solutions [4].

RAP has become a vital component in asphalt pavement construction due to its significant economic and environmental advantages [5]. RAP materials consist of processed materials containing aged bitumen and aggregates from old pavements, which are then reused in new asphalt mixtures [6–8]. Utilizing RAP in pavement construction not only conserves natural resources but also reduces the amount of construction waste deposited in landfills, leading to more sustainable pavement management practices, and lowered greenhouse gas emissions [9,10]. However, RAP sourced from different depots and stockpiles often exhibits significant variations, making it nearly impossible to guarantee consistent material availability for experiments [11–13]. Additionally, incorporating high percentages of RAP into asphalt mixtures poses challenges due to the aged bitumen present in RAP [14]. Aged bitumen tends to be stiffer and more brittle than virgin bitumen, which can negatively impact the performance of the asphalt mixture [15,16]. The RAP binder can exhibit higher stiffness, leading to increased brittleness, reduced flexibility, and a higher susceptibility to cracking [17–19]. Therefore, improving the properties of asphalt mixture with high RAP content is crucial to ensure their durability and performance [20,21].

Several studies have explored the impact of RAP on asphalt mixture performance [22]. For instance, Basueny et al. examined the mechanical properties of asphalt mixtures containing different RAP contents and found that mixtures with higher RAP content showed reduced fatigue resistance and increased stiffness [23]. Similarly, Li et al. evaluated the effects of RAP on the cracking behavior of asphalt mixtures, highlighting the negative impact of aged RAP on fracture resistance [24]. While the use of RAP has clear advantages, its age is an additional factor that influences the performance of asphalt mixtures. However, the influence of RAP age, especially the differentiation between RAP that has been aged for 5 years versus 10 years, is less explored, with only a few studies investigating the differences between 5-year and 10-year-old RAP materials [15,25,26]. The age of RAP plays a significant role in the stiffness and brittleness of the mixture, and it is important to investigate how the performance of asphalt mixtures changes when different ages of RAP are incorporated [27]. Pradhan found that mixtures with older RAP material exhibited worse cracking resistance due to the aging and hardening of the binder [28].

One of the potential solutions to mitigate the adverse effects of aged RAP is the incorporation of nano materials [29–31]. Nano-silica (SiO_2) is one of useful case of these materials [30,32]. Given its small size and large surface area, nano-silica interacts with the asphalt binder at the molecular level [33,34], potentially offsetting the negative effects of aging and providing superior performance, particularly in mixtures containing RAP. Nano-SiO_2, with these physical and chemical properties, has been shown to improve the performance of asphalt mixtures by enhancing the binder's adhesion properties, reducing aging effects, and increasing the mixture's resistance to cracking and fatigue [35,36]. The incorporation of nano-silica into asphalt binders has been shown to improve key performance parameters, such as fracture resistance, fatigue life, and moisture susceptibility [37]. For example, Adamu et al. demonstrated that the addition of nano-silica to asphalt binder significantly improved the fatigue resistance of asphalt mixtures [38]. Similarly, Mirabdolazimi et al. investigated the role of nano-silica in improving the moisture resistance of asphalt mixtures, showing that nano-silica could reduce the damage caused by water-induced deterioration [39]. Other studies, such as that by Shafabakhsh et al., demonstrated that nano-silica improved the low-temperature performance of asphalt mixtures [40].

While numerous studies have explored the effects of RAP content and aging on asphalt mixtures, and others have investigated the role of nano-silica, limited research has been conducted on the combined effects of varying RAP content, RAP age, and nano-silica addition. Few studies have comprehensively assessed these factors together using multiple performance tests, such as fracture resistance, fatigue performance, and moisture susceptibility. Furthermore, the role of RAP age in this context remains underexplored, and there is a gap in understanding how nano-silica can mitigate the effects of both high RAP content and the aging of RAP materials. The rehabilitation and maintenance of aging pavement infrastructure are critical challenges in modern civil engineering. The reuse of RAP has gained significant attention due to its potential for cost reduction, resource conservation, and environmental benefits. However, concerns regarding the mechanical performance and long-term durability of RAP-incorporated mixtures necessitate further investigation. This study explores the use of nano-silica as a modification strategy to enhance the fatigue resistance, fracture toughness, and moisture susceptibility of RAP-modified asphalt mixtures. The findings provide valuable insights for optimizing the use of recycled materials in pavement rehabilitation projects, contributing to more sustainable and resilient road infrastructure. Therefore, this study seeks to address these gaps by comprehensively evaluating the combined effects of RAP content (25%, 50%, 75%), RAP age (5 years and 10 years), and nano-silica content (0%, 1%, 1.5%, and 2%) on asphalt mixture performance. The study will focus on key performance indicators such as fracture resistance (using the SCB test), fatigue resistance (using the ITF test), and moisture susceptibility (using the TSR test). The goal is to provide a holistic understanding of how these factors interact and identify the optimal combination of RAP and nano-silica for high-performance asphalt mixtures.

2. Materials and test method

2.1. Nano silicon dioxide (SiO_2)

Nano-SiO_2, consisting of silicon and oxygen, is known for its high reactivity due to its large surface area. It plays a crucial role in construction materials, particularly in enhancing adhesion and filling properties. In this research, based on the findings of previous studies, the optimal amount of Nano silicon dioxide selected for its significant effect on bitumen aging is 1.5% [41,42]. Its characteristics are presented in the Table 1. To account for variations in the performance of modified bitumen, two additional percentages of Nano- SiO_2 (1% and 2%) are also utilized.

Table 1. Characteristics of Nano- SiO2 used in this study.

Characterization	Quantity
Chemical formula	SiO2
Specific gravity (g/cc)	2.4
Particle size (Nm)	80
Color	white
Morphology	spherical
Specific surface area (m2/g)	160
Degree of purity (%)	99.9
Water absorption (%)	<0.2

These nanomaterials can be introduced as dry powders or suspended in a liquid solvent. The chosen solvent must dissolve well in bitumen at low to medium temperatures, evaporate quickly, and not significantly affect bitumen’s mechanical properties. Additionally, it should have low viscosity at ambient temperature to ensure uniform dispersion of the nanomaterials. Various solvents, such as Kerosine, Warsel, Turpentine, and Acetone have these properties [40,42]. In this research, consistent with previous studies, Kerosine solvent, is utilized to disperse nanomaterials in bitumen. The choice of Kerosine is attributed to its cost-effectiveness and availability, as well as its petroleum-based nature, which minimizes adverse effects on the chemical structure of bitumen.

2.2. Bitumen

In this study, a bitumen with a penetration grade of 60/70 (PG 64-16) was utilized. The specifications of this bitumen are detailed in Table 2.

Table 2. Specifications of neat bitumen used in this study.

Test	Unit	Standard	Quantity
Specific gravity	-	ASTM D-70	1.03
Penetration (100 g, 5 s, 25°C)	0.1 (mm)	ASTM D5-73	65
Softening point	(°C)	ASTM D36-76	51
Flash point	(°C)	ASTM D92-78	283
Viscosity @ 135°C	(mPa.s)	ASTM D4402	431
Ductility (25°C, 5 cm/min)	(cm)	ASTM D113-79	>100
Loss of heating	(%)	ASTM D1754-78	0.74

To ensure the uniform dispersion of nanomaterials in the modified bitumen, penetration and softening point tests were conducted on three sections of a cylindrical sample: top, middle, and bottom. The variation in softening point results was less than 1°C, and the difference in penetration values was less than 0.2 mm. These results indicate that the nanomaterials were well distributed throughout the bitumen sample.

2.2. Aggregate

The limestone aggregate was utilized to fabricate the asphalt mixtures. For this purpose, the gradation curve of Fig. 1, with maximum aggregate size of 19 mm, was considered.

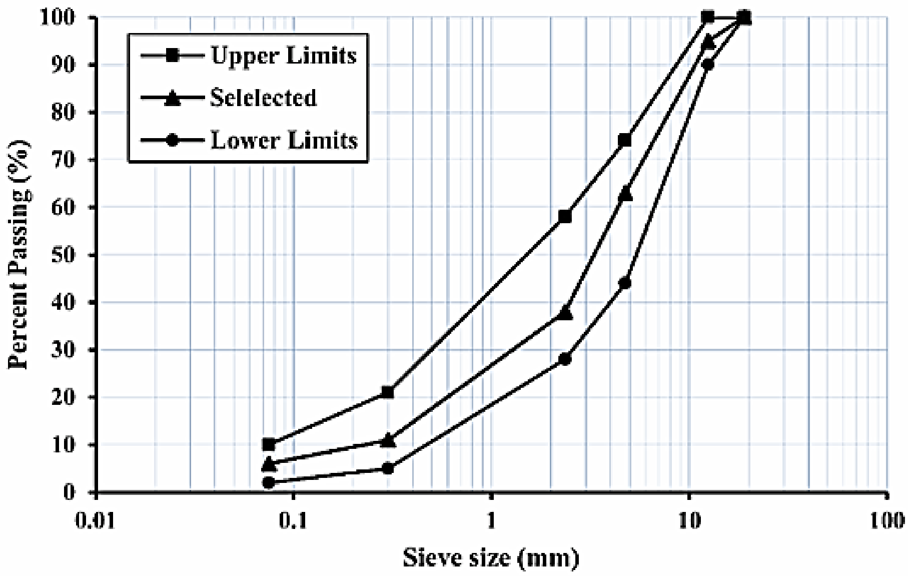

Fig. 1. The gradation curves used in this study.

2.3. RAP material

Two types of RAP materials were obtained from the municipal asphalt production plant located in Tehran. Based on the documented records of their extraction from urban roads, the first type has an aging period of 5 years, while the second type has an aging period of 10 years.

3. Test method

3.1. Mix design

In accordance with ASTM D1559 standard [43], a range bitumen percentages of 4 to 6 percent were used to prepare Marshall samples. To compact these samples, 75 blows were applied to simulate the heavy traffic loading. Finally, the optimal bitumen content for the control asphalt mixture was determined to be 4.6 percent. This bitumen percentage was also applied to modified asphalt mixtures, and all mix design parameters were controlled. Two types of RAPs with different ages of 5 and 10 years old with three portions of 25, 50, and 75% were employed to fabricate the other mix types. It should be noted that the optimum bitumen content of cases including RAP, was determined based on the extraction test and related protocol of mix design for recycled asphalt pavement. The labeling system was considered for different mixture types as shown in Table 3.

Table. 3. Labeling system for different mixture types.

Sample Code	Content of RAP-5 years old (% by total weight.)	Content of RAP-10 years old (% by total weight.)	Nano- SiO_2 content (% by total weight. of bitumen)	Optimum bitumen content (%)
C-N0	0	0	0	4.6
C-N1	0	0	1	4.6
C-N1.5	0	0	1.5	4.6
C-N2	0	0	2	4.6
RA25-N0	25	0	0	3.6
RA25-N1	25	0	1	3.6
RA25-N1.5	25	0	1.5	3.6
RA25-N2	25	0	2	3.6
RA50-N0	50	0	0	3.2
RA50-N1	50	0	1	3.2
RA50-N1.5	50	0	1.5	3.2
RA50-N2	50	0	2	3.2
RA75-N0	75	0	0	2.5
RA75-N1	75	0	1	2.5
RA75-N1.5	75	0	1.5	2.5
RA75-N2	75	0	2	2.5
RB25-N0	0	25	0	3.8
RB25-N1	0	25	1	3.8
RB25-N1.5	0	25	1.5	3.8
RB25-N2	0	25	2	3.8
RB50-N0	0	50	0	3.5
RB50-N1	0	50	1	3.5
RB50-N1.5	0	50	1.5	3.5
RB50-N2	0	50	2	3.5
RB75-N0	0	75	0	3.0
RB75-N1	0	75	1	3.0
RB75-N1.5	0	75	1.5	3.0
RB75-N2	0	75	2	3.0

3.2. Semi-circular bending test

The semi-circular bending (SCB) test [44] aims to assess the fracture resistance of asphalt mixtures by determining the critical strain energy release rate. This parameter is called the critical value of J-integral (J_c) and it is influenced by the rate of strain energy change per notch depths (d_U/d_a), as indicated in Eq. (1). This value reflects the strain energy consumed during the formation of a fractured surface in asphalt mixture. Higher J_c values signify greater toughness in resisting cracking and crack propagation.

$$J_c = -\frac{1}{t} \times \left(\frac{d_U}{d_a}\right) \tag{1}$$

where, J_c represents the critical strain energy release rate in units of kJ/m^2, ‘b’ denotes the sample thickness in meters, ‘a’ stands for the notch depth in meters, and ‘U’ represents the strain energy to failure in either kN-m or kJ.

In order to calculate Jc, specimens with three different notch depths are utilized. The 3-point bending test configuration and typical specimen dimensions of the SCB test are depicted in Fig. 2. The test is carried out for three replicate specimens, for each notch depth at 25°C. Notch depths of 25.4, 31.8, and 38.0 mm are typically chosen based on the 'a/rd' ratio. The use of three notch depths enhances the accuracy of Jc calculation, even though the rate of strain energy change per notch depth (dU/da) can be computed with only two different notch depths.

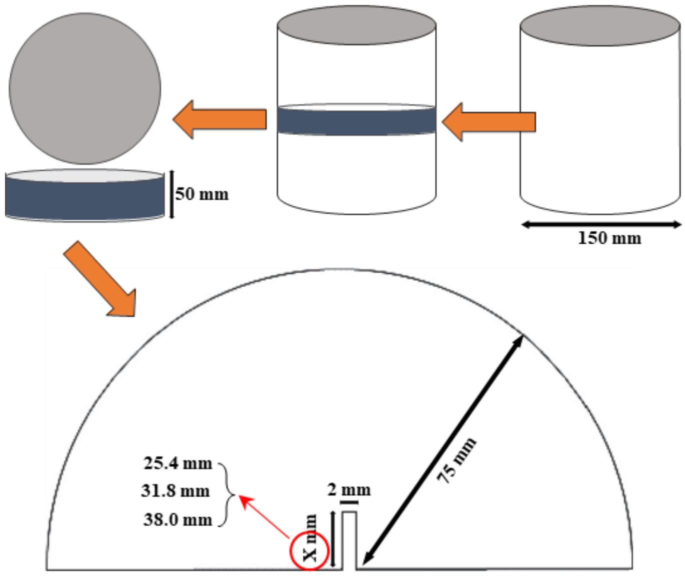

Fig. 2. Procedure of sample preparation for SCB test.

The SCB specimens are subjected to a constant cross-head deformation rate of 0.5 mm/min and loaded monotonically on an UTM until fracture failure occurs. Throughout the test, the load and deformation data are continuously recorded and utilized to produce a series of load versus deformation curves, from which the critical value of Jc is determined using Eq. (1).

3.3. ITS test

The examination of moisture damage in Marshall samples containing 7% air voids was performed utilizing the modified Latman standard AASHTO T283 [45]. The samples were categorized into conditioned and unconditioned groups, with the conditioned samples undergoing a freeze-thaw cycle. Subsequently, the moisture durability of the samples was assessed by calculating the tensile strength ratio (TSR), as indicated in Eq. (2).

$$TSR = \frac{ITS_{Conditioned}}{ITS_{Unconditioned}} \times 100 \tag{2}$$

The indirect tensile strengths of the conditioned and unconditioned samples are referred to as ITSConditioned and ITSUnconditioned, respectively. The maximum load exerted on the sample is denoted by P, while the sample's diameter and thickness are represented by d and t, respectively.

3.4. Indirect tensile fatigue test

The fatigue life of asphalt mixtures was evaluated using the indirect tensile fatigue (ITF) test. This method applies vertical compressive loads to a cylindrical specimen (with an air void of 4%), generating uniform tensile stresses along the vertical diametrical plane. As a result, horizontal tensile stresses and strains develop, leading to fatigue failure under repeated loading. Fatigue life is defined as the number of load cycles required to reach failure, as specified by the EN 12697-24 standard [46]. Tests were conducted at three constant stress levels of 400, 500, and 600 kPa and a temperature of 20°C, with a haversine loading frequency of 2 Hz (0.1 s loading, 0.4 s rest). The relationship between tensile stress (σ_t) and the number of load cycles to failure (N_f) was determined through regression analysis, as shown in Eq. (3):

$$N_f = K_1.(\sigma_t)^{-K_2} \tag{3}$$

where N_f is the fatigue life (cycles to failure), σ_t is the applied stress, and K_1 and K_2 are constants.

4. Results and discussion

This section first examines the potential of bitumen modification process by nano materials to assess the cracking resistance of mixtures throughout the SCB test. After that, it investigates the moisture durability of different types of asphalt mixtures using ITS test. Finally, the results of fatigue performance of control and modified mixtures will be evaluated by ITF test. In addition, a statistical analysis will be performed for different mixture types to find the most important parameters during this modification.

4.1. SCB results

The critical J-integral was employed to assess the fracture resistance of asphalt mixtures at 25°C, considering various RAP percentages, RAP ages, and Nano-SiO_2 dosages. The fracture results of three notch depths of 25.4, 31.8, and 38.0 mm was used to calculate this index for each mix type, the results of which are shown in Fig. 3.

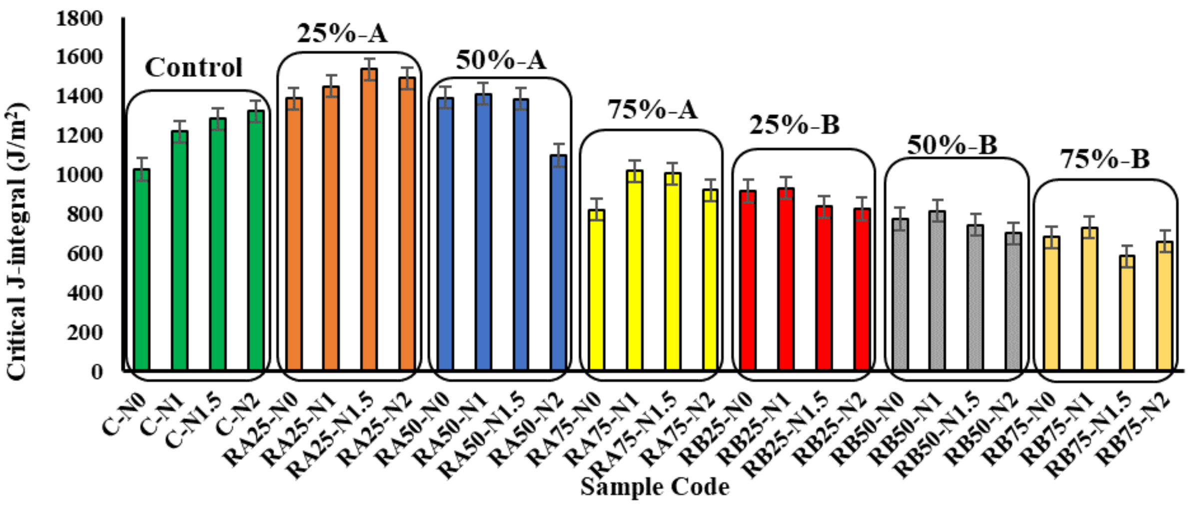

Fig. 3. The results of J-integral for different mixture types at 25°C.

The control mixture (neat asphalt without RAP) exhibited moderate fracture resistance values ranging from 1100 to 1300 J/m². This served as the baseline for evaluating the performance of RAP-modified mixtures. The inclusion of RAP significantly influenced the fracture resistance, with variations depending on the RAP content and age. At 25% RAP, the fracture resistance improved substantially, with Type A mixtures (5-year-old RAP) showing the highest increase of approximately 25–30% compared to the control. Type B mixtures (10-year-old RAP) also outperformed the control, though the improvement was less pronounced (10-15%).

As the RAP content increased to 50%, a slight reduction in fracture resistance was observed compared to 25% RAP mixtures. Despite this, the fracture resistance of Type A mixtures remained approximately 15-20% higher than the control, whereas Type B mixtures showed a marginal improvement of 5-10%. At 75% RAP, however, a significant deterioration in fracture resistance occurred, particularly in Type B mixtures, where values dropped below those of the control mixture by 10-15%. Type A mixtures, although affected, maintained fracture resistance comparable to or slightly above the control (5-10% higher). These results highlight the adverse impact of high RAP content, especially when older RAP materials are used.

The incorporation of Nano-SiO_2 was shown to effectively enhance fracture resistance across all RAP percentages and types. The improvement was most pronounced in mixtures with lower RAP content (25% and 50%). For example, at 25% RAP, increasing the SiO_2 content from 0% to 2% resulted in an additional 20-25% increase in fracture resistance. At 50% RAP, the improvement was slightly lower but still significant, ranging from 15-20%. Even at 75% RAP, where fracture resistance was generally reduced, the addition of Nano-SiO_2 mitigated the negative effects, leading to a recovery of 10-15% compared to mixtures without the additive. The effect of Nano-SiO_2 was particularly beneficial for Type B mixtures, compensating for the reduced fracture resistance caused by the aging of RAP materials.

Moreover, the results presented in Fig. 3 represent the average of three repetitions, with error bars included in the figure. These error bars indicate that the variations in the experimental results are due to the addition of additives to the asphalt mixture, rather than laboratory errors.

4.2. Moisture susceptibility

The indirect tensile strength (ITS) of asphalt mixtures was evaluated under dry and wet conditions, as shown in Fig. 4. The results demonstrate the effects of RAP content, RAP age, and Nano-SiO_2 dosage on the ITS, providing insights into the moisture susceptibility and overall strength of the mixtures.

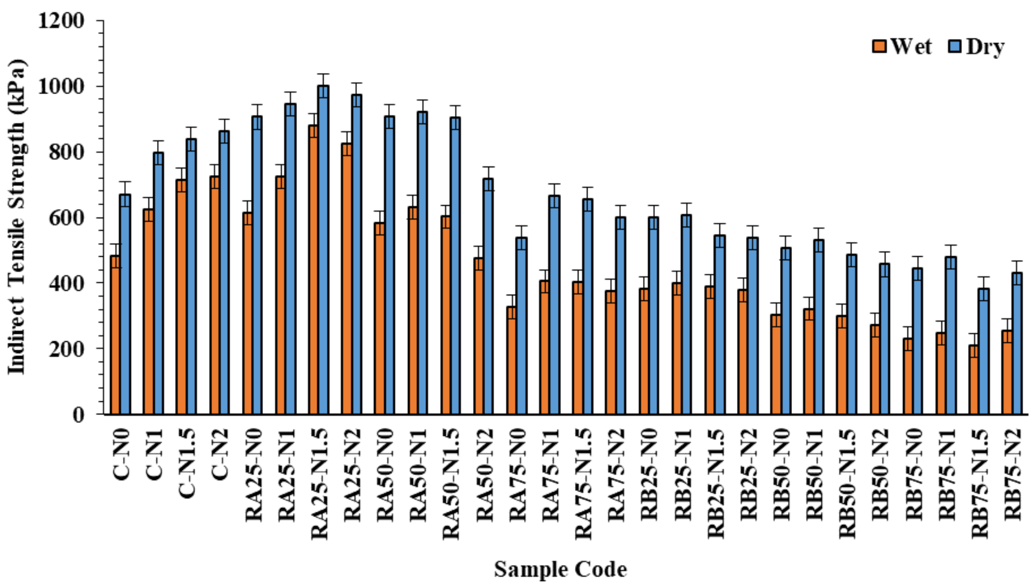

Fig. 4. The results of indirect tensile strength of different mixtures.

The control mixture (C) exhibited moderate ITS values in both dry and wet conditions, with the ITS in dry conditions approximately 40–50% higher than in wet conditions. This baseline comparison highlights the inherent moisture susceptibility of asphalt without RAP or Nano-SiO_2 additives. The addition of RAP significantly affected ITS, with variations depending on RAP percentage and age. At 25% RAP, the ITS in dry conditions improved by 20–25% compared to the control mixture for Type A (5-year-old RAP) and by 10–15% for Type B (10-year-old RAP). Under wet conditions, the improvement was less pronounced, with increases of 10–15% and 5–10% for Types A and B, respectively.

As the RAP content increased to 50%, the ITS in both dry and wet conditions showed a slight decline compared to 25% RAP mixtures. However, the values remained higher than the control, particularly for Type A mixtures, where the ITS under dry conditions was approximately 10–15% higher than the control. At 75% RAP, a noticeable reduction in ITS was observed in both dry and wet conditions, with values for Type B mixtures dropping below the control by approximately 10–20%. This reduction highlights the adverse effects of high RAP content and aged RAP materials on the tensile strength of asphalt mixtures.

The incorporation of Nano-SiO_2 proved to be effective in enhancing ITS across all RAP levels and conditions. For 25% RAP mixtures, the addition of 2% Nano-SiO_2 increased the ITS by 15–20% under dry conditions and by 10–15% under wet conditions compared to mixtures without the additive. Similar trends were observed for 50% RAP mixtures, where the ITS increased by approximately 10–15% in both conditions. At 75% RAP, the addition of Nano-SiO_2 mitigated the reduction in ITS, recovering up to 10–15% of the lost strength under both conditions. This improvement was particularly significant for Type B mixtures, where the ITS under wet conditions approached or exceeded the values of the control mixture. However, relying solely on ITS values under dry and wet conditions may not provide a comprehensive evaluation of the performance of asphalt mixtures, especially their resistance to moisture-induced damage. To address this, the tensile strength ratio (TSR) is considered a more reliable parameter for comparing and assessing the moisture susceptibility of the mixtures. The TSR results are presented in Fig. 5, providing further insights into the effectiveness of RAP content and Nano-SiO_2 additives in enhancing the durability of asphalt mixtures under moisture exposure.

It should be noted that the results of ITS values shown in Fig. 4 represent the average of three repetitions, with error bars illustrating the variability. These error bars confirm that the observed differences in the experimental results stem from the influence of additives in the asphalt mixture, rather than inconsistencies in laboratory procedures.

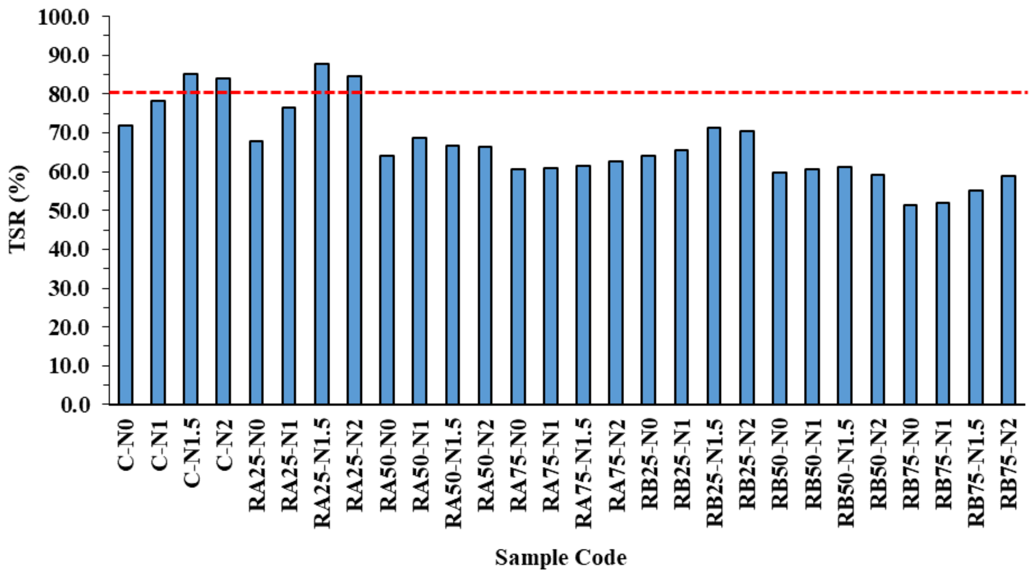

Fig. 5. The results of TSR for different mixture types.

As shown in Fig. 5, the TSR results provide valuable insights into the performance of different mixtures, including the control, mixtures containing various percentages of RAP, RAP age, and the addition of Nano-SiO_2. The control mixture (C) displayed TSR values ranging from approximately 70–85%, with the addition of Nano-SiO_2 having a noticeable positive impact. Specifically, the control mixture with no Nano-SiO_2 (C-N0) achieved a TSR of around 70%, which increased to over 80% with the inclusion of 1.5% and 2% Nano-SiO_2. This enhancement highlights the potential of Nano-SiO_2 to improve moisture resistance in neat asphalt mixtures, enabling them to meet the commonly recommended threshold of 80% for TSR. For mixtures incorporating RAP, the TSR results varied depending on the RAP content and age. At 25% RAP, the TSR values ranged from approximately 75–85%. Mixtures with Type A RAP (5 years old) exhibited slightly higher TSR values compared to those with Type B RAP (10 years old), indicating better moisture resistance for less aged RAP materials. The addition of Nano-SiO_2 further improved the TSR values, with mixtures containing 1.5% and 2% Nano-SiO_2 achieving TSR values consistently above the 80% threshold, regardless of RAP type.

As the RAP content increased to 50%, the TSR values declined significantly and remained within the range of 60-70% for most mixtures. Mixtures with Type A RAP maintained superior performance compared to those with Type B RAP, particularly when Nano-SiO_2 was added. Notably, 2% Nano-SiO_2 improved the TSR values of 50% RAP mixtures by 5–10%, enabling some mixtures to approach the 80% threshold. At 75% RAP, the TSR values showed a more pronounced decline, particularly for mixtures with Type B RAP. Without Nano-SiO_2, the TSR values for all mixtures fell below the 80% threshold, indicating increased susceptibility to moisture-induced damage. However, the addition of Nano-SiO_2 mitigated this decline, with mixtures containing 1.5% and 2% Nano-SiO_2 recovering up to 10% in TSR values. Despite this improvement, only a limited number of 75% of RAP Type A mixtures managed to meet or exceed the 60 percentage.

4.3. Fatigue results

The ITF test was conducted on various mixture types to investigate the fatigue performance of different combinations of RAP and nano materials at intermediate temperature of 20°C using UTM device, according to EN 12697-24 standard. The Wohler diagram was depicted to find the related parameters of fatigue equation. These results are shown in Fig. 6 and for mixtures without RAP materials.

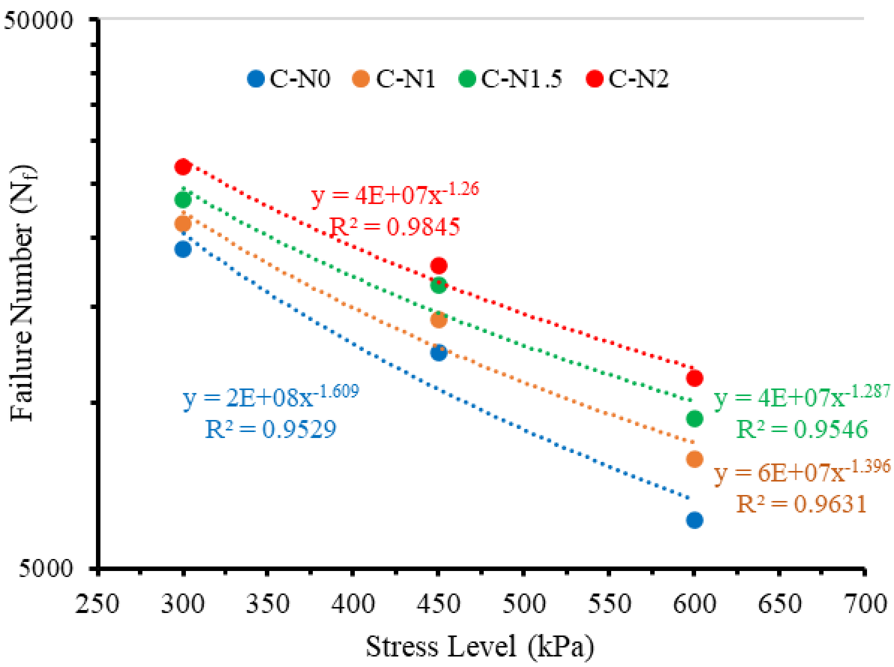

Fig. 6. The Wohler diagram for different mixture types without RAP.

This figure illustrates the number of failures versus the applied stress level for mixtures without RAP. The results reveal that the control sample (C-N0) without any modifier exhibits the lowest Nf across all stress levels, indicating its poor resistance. Moreover, the addition of Nano-SiO_2 significantly enhances the fatigue performance of the asphalt mixtures. In addition, the results of Wohler diagram were obtained for those mixtures containing the RAP, shown in Fig. 7.

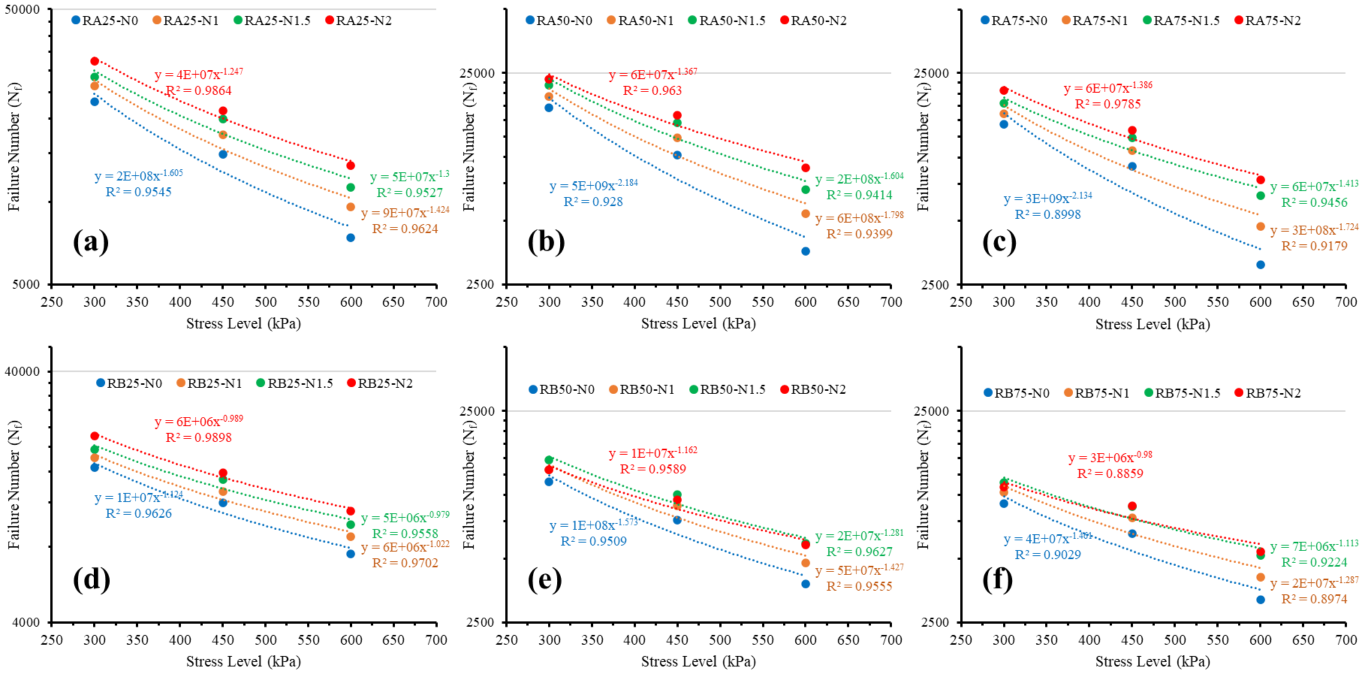

Fig. 7. The Wohler diagram for different mixtures containing a) 25% RAP-A, b) 50% RAP-A, c) 75% RAP-A, d) 25% RAP-B, e) 50% RAP-B, and f) 75% RAP-B.

The results in Fig. 7 indicate that, for each RAP content, the fatigue performance of the mixture varies depending on the effect of bitumen modification. The use of 25% Type A RAP results in the most significant improvement in fatigue performance across all stress levels and bitumen modification methods. Specifically, at this RAP content (25%), incorporating 2% nano-materials achieves the best performance compared to other dosages. However, higher contents of Type A RAP exhibit a decreasing trend in fatigue performance. Overall, the results in Fig. 7 demonstrate that Type A RAP outperforms Type B RAP. Additionally, for high percentages of Type B RAP (50% and 75%), an optimal bitumen modification dosage of 1.5% is observed. It is also evident that increasing the level of applied stress reduces the fatigue life. Further investigation is required to derive the fatigue equation for each mixture type to gain deeper insights. The provided Table 4 summarizes the fatigue performance parameters K_1 and K_2 for various asphalt mixtures, offering insights into the effects of RAP, RAP aging, and nano-silica modification on fatigue life. The trends observed in the fatigue equation reveal critical findings regarding the balance between performance improvement and potential trade-offs.

The control mixture (C-N0) serves as a baseline, exhibiting specified fatigue resistance under low-middle-high stress levels. However, its performance diminishes rapidly as stress levels increase, making it a reference point for evaluating modifications.The incorporation of RAP enhances fatigue performance at low stress levels but introduces a trade-off under higher stresses. For mixtures with 25% RAP, K1 and K2 improves by approximately 15%-20%, indicating increased resistance to fatigue. However, a slight rise in K1 and K2 (up to 10%) reflects a faster reduction in performance as stress increases.At 50% RAP, the reduction in K1 and K2 becomes pronounced, reaching up to 35%, and this is accompanied by a 15%-20% decreasing in K1 and K2, demonstrating a steep decline in fatigue life under high stresses. Mixtures with 75% RAP exhibit the lowest K1 and K2 values, with reduction of up to 50%, limiting their effectiveness under severe conditions.

Aging of the RAP material significantly impacts fatigue performance. The use of 10-year-old RAP (Type B) results in a 10%-15% reduction in K1 and K2 compared to 5-year-old RAP (RA series), highlighting the negative influence of increased stiffness and brittleness. Additionally, K1 and K2 values for aged RAP mixtures decrease by 10%-20%, further reducing their durability under stress. For example, according to Table 4, the mixture of Type B, with 75% of RAP, shows the worse fatigue performance, indicated by a low K1 value and a high negative K2 value, reflecting its poor performance.

Table. 4. Information of fatigue equation (Nf = K1×[σt]-K2) for different mixtures.

Sample Code	RAP type	RAP%	Nano- SiO_2 %	Fatigue Coefficients	
				K_1	K_2
C-N0	-	0	0	2E+08	-1.609
C-N1			1	6E+07	-1.396
C-N1.5			1.5	4E+07	-1.287
C-N2			2	4E+07	-1.260
RA25-N0	A	25	0	2E+08	-1.605
RA25-N1			1	9E+07	-1.424
RA25-N1.5			1.5	5E+07	-1.300
RA25-N2			2	4E+07	-1.247
RA50-N0		50	0	5E+09	-2.184
RA50-N1			1	6E+08	-1.798
RA50-N1.5			1.5	2E+08	-1.604
RA50-N2			2	6E+07	-1.367
RA75-N0		75	0	3E+09	-2.134
RA75-N1			1	3E+08	-1.724
RA75-N1.5			1.5	6E+07	-1.413
RA75-N2			2	6E+07	-1.386
RB25-N0	B	25	0	1E+07	-1.124
RB25-N1			1	6E+06	-1.022
RB25-N1.5			1.5	5E+06	-0.979
RB25-N2			2	6E+06	-0.989
RB50-N0		50	0	1E+08	-1.573
RB50-N1			1	5E+07	-1.427
RB50-N1.5			1.5	2E+07	-1.281
RB50-N2			2	1E+07	-1.162
RB75-N0		75	0	4E+07	-1.461
RB75-N1			1	2E+07	-1.287
RB75-N1.5			1.5	7E+06	-1.113
RB75-N2			2	3E+06	-0.98

The addition of nano-silica demonstrates a clear ability to enhance fatigue performance, particularly when combined with RAP. Mixtures modified with 1% nano-silica show a 10%-15% improvement in K1 and K2, partially offsetting the adverse effects of high RAP content or aging. A further increasing in K1 and K2 enhances durability under higher stress levels. Increasing the nano-silica content to 1.5% yields even more significant improvements, with K1 and K2 increasing by 20%-30%. The highest dosage of nano-silica (2%) leads to substantial improvements, with K1 and K2 increasing by up to 50%, resulting in exceptional fatigue resistance under varying stress conditions. The combination of RAP and nano-silica shows synergistic benefits, particularly for mixtures with moderate RAP content (25%-50%). These mixtures exhibit balanced fatigue performance, with high K1 and K2 values ensuring resistance under repeated loading. For mixtures with 75% RAP, nano-silica mitigates some of the negative effects, but the inherent trade-offs remain significant, emphasizing the challenges of excessive RAP content.

4.4. Statistical analysis

Analysis of Variance (ANOVA) analysis, with a 95 % confidence interval, is performed to evaluate the impact of RAP Type, RAP content, and modification process on the mechanical properties of the asphalt mixture. The indices such as P-value and F-value are provided for the final result of ITS test, SCB test, and ITF test, shown in Table 5. The P-value represents the probability that the observed results occurred by chance, with a lower P-value indicating stronger statistical significance. The F-value is the test statistic for ANOVA, which compares variance between groups to variance within groups to determine if there are significant differences. It is tried to interpret the results by checking whether there is a statistically significant difference among the material properties of the seven mixture types (e.g., Control, RA with 25%, 50%, 75%, and RB with 25%, 50%, 75%).According to One-Way ANOVA approach, two hypothesizes are considered. For example, for SCB result, i.e., J-integral, these hypothesizes are; 1- Null Hypothesis (H0): There is no significant difference in the mean J-integral values between the mixture types, and 2- Alternative Hypothesis (Ha): There is a significant difference in the mean J-integral values between at least two mixture types. For this purpose, the data were grouped by mixture type. Then, the mean and variance of J-integral values for each group were calculated. Finally, the One-Way ANOVA test was performed to provide the F-Statistic and P-value.

Table 5. The ANOVA analysis of mechanical properties of various mixtures.

Material Properties	Source	Degree of Freedom	Sum of Square	Mean Square	F Statistic	P-value
J-integral	Groups (between groups)	5	2.03E+06	4.06E+05		
	Error (within groups)	18	1.30E+05	7.22E+03	56.2226	2.349e-10
	Total	23	2.16E+06	9.40E+04		
TSR	Groups (between groups)	5	1.44E+03	2.88E+02		
	Error (within groups)	18	3.25E+02	1.81E+01	15.919	0.00000464
	Total	23	1.76E+03	7.67E+01		
Fatigue life (N_f)	Groups (between groups)	5	7.18E+08	1.44E+08		
	Error (within groups)	18	1.16E+08	6.44E+06	22.2864	3.928e-7
	Total	23	8.34E+08	3.63E+07		

Since the p-value is far below the significance level of α = 0.05, the null hypothesis is rejected, concluding that there are significant differences between the group means. In addition, the critical F-value, based on the degrees of freedom (dfbetween=6, dfwithin=21) and α=0.05, is 2.57. The computed F-Statistic exceeds this critical value, further confirming significant differences between the groups. Overall, according to ANOVA analysis, RAP material has a significant impact (P-value less than 0.05) on all mixture performances. This indicates that adding RAP leads to significant changes in cack resistance, moisture susceptibility, as well as in fatigue life. Similar to RAP, Type of this recycled material and the additive also have a significant effect (P-value less than 0.05) on performance of mixtures. This shows that adding Nano-SiO2 also causes substantial changes in the mechanical properties of the asphalt mixture. The ANOVA results and group means clearly highlight that both the type of modification and the RAP Type significantly influence the J-integral, TSR, and Nf values. Type A RAP mixtures, especially with lower percentages (25% and 50%), show enhanced performance, while Type B RAP mixtures demonstrate diminishing performance as its content increases. In other words, these changes and improvements are due to the use of the nano and RAP materials and not due to experimental error.

4. Summary and conclusion

This study investigates the effects of Nano-SiO_2 modification on asphalt mixtures incorporating RAP with two distinct aging levels (5 years and 10 years). The objective is to evaluate the interaction of Nano-SiO_2 and RAP content to identify optimal combinations that enhance fracture resistance, moisture durability, and fatigue performance of asphalt mixtures. Through SCB, ITS, and ITF tests, the study assesses cracking resistance, moisture susceptibility, and fatigue life, respectively, while also employing statistical analyses to determine the key factors influencing these properties. A summary of the results of the current study are presented as follow:

- **Fracture resistance:** The control mixture exhibited values between 1100 and 1300 J/m². Adding 25% RAP provided the best performance, improving resistance by 25–30% for 5-year-old RAP and 10–15% for 10-year-old RAP. At 50% RAP, improvements were still observed (15–20% for 5-year-old RAP), but 75% RAP significantly reduced resistance. Nano-SiO_2 enhanced fracture resistance at all RAP levels, recovering 10–25% of lost performance, with the most significant effect on aged RAP mixtures.
- **Moisture resistance:** The control mixture had TSR values between 70–85%. Increasing RAP content and aging reduced TSR, with 75% RAP falling below the 80% threshold. Nano-SiO_2 improved TSR across all mixtures, increasing values by 5–15% and allowing even high-RAP mixtures to achieve acceptable moisture resistance.
- **Fatigue performance:** The control mixture performed well at low stresses but weakened under high stresses. Adding 25% RAP improved fatigue resistance at low stresses (15–20%) but slightly reduced it at higher stress levels. Higher RAP contents (50–75%) significantly decreased fatigue life, with K1 and K2 values dropping by up to 50%. Nano-SiO_2 mitigated this decline, improving fatigue performance by up to 50%, especially in mixtures containing 25–50% RAP.
- **Statistical analysis:** ANOVA results showed that mixtures with 25% RAP (5-year-old) and 1.5% Nano-SiO_2 had the best overall mechanical performance, followed by the control and 50% RAP mixtures. In contrast, 75% RAP mixtures exhibited the lowest resistance. The results highlight the importance of optimizing RAP and Nano-SiO_2 contents to achieve balanced performance.

Overall, the study confirms that incorporating 25–50% RAP with 1.5% Nano-SiO_2 provides a well-balanced mix with improved durability, fracture, moisture, and fatigue resistance, making it a promising solution for sustainable asphalt pavement design.

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Authors contribution statement

Esmaeil Taheri: Writing Original Draft, Formal analysis, Visualization, Resources, Experimental Investigation, Software.

Gholamali Shafabakhsh: Project Administration, Supervision, Conceptualization, Methodology, Writing - Review & Editing.

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

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