ORIGINAL RESEARCH

Numerical Simulation of the Mechanical Behavior of Steel and Macrosynthetic Fiber-Reinforced Asphalt Concrete Using the Finite Element Method in ABAQUS

hamed taghavi*[1], Shima Aghakasiri [1]

[1] Department of Civil Engineering, S.T.C, Islamic Azad University, Tehran (Iran)

hamedtaghavi98@gmail.com
sh.aghakasiri@iau.ir

*Correspondence: hamedtaghavi98@gmail.com

Received:2025/11/09 ; **Accepted:** 2025/12/22 ; **Published:**

Citation: Taghavi, H. Agha kasiri, Sh. (2025). Numerical Simulation of the Mechanical Behavior of Steel and Macrosynthetic Fiber-Reinforced Asphalt Concrete Using the Finite Element Method in ABAQUS. https://doi.org/

Abstract: In this study, the effect of fiber type and volume fraction on the mechanical behavior of asphalt concrete was investigated using the finite element method (FEM) and the Concrete Damaged Plasticity (CDP) model in ABAQUS software. To this end, asphalt concrete specimens without fibers, with macrosynthetic polyacrylonitrile (PAN) fibers, and with steel fibers at volume fractions of 0.2% and 0.4% were modeled. The results of stress contours and load–displacement curves indicated that increasing the fiber content enhances the ultimate strength and reduces stress concentration in the crack zone. Steel fibers, by forming stress transfer bridges in the failure region, provided the greatest increase in strength specifically, the ST0.4% model exhibited a 31.5% improvement in strength compared to the reference specimen. On the other hand, PAN fibers increased toughness and crack energy absorption, resulting in more ductile behavior and delayed crack propagation particularly in the PAN0.4% model, where fracture stability and uniform stress distribution were significantly improved. Furthermore, validation of the numerical model against experimental data from the literature (Gao et al., 2021) showed an error below 5%, confirming the accuracy and reliability of the developed model. Accordingly, the selection of fiber type should be based on the design objective: steel fibers are recommended for strength enhancement, while PAN fibers are more suitable for improving durability and crack control.

Keywords: Asphalt concrete, steel fibers, macrosynthetic fibers, CDP model, stress contour, fracture stability.

Highlights:

- Numerical simulation of fiber-reinforced asphalt concrete behavior using the Concrete Damaged Plasticity (CDP) model.
- Investigation of two fiber types (steel and macrosynthetic PAN) at two different volume fractions.
- 3D modeling using C3D8R elements and random fiber distribution within the specimen volume.
- Validation of the numerical model with experimental data (Gao et al., 2021).
- Extraction of load–displacement curves, stress distribution and failure patterns for each model.
- Comparative analysis of toughness mechanisms and crack-resistance.

1. Introduction

Asphalt concrete is a heterogeneous composite material extensively used in pavement engineering due to its flexibility, energy dissipation capacity, and constructability. Nevertheless, conventional asphalt mixtures are prone to cracking, rutting, and fatigue damage under repetitive traffic loading and environmental effects, which are mainly attributed to stress concentration, limited tensile capacity, and inadequate crack resistance. These shortcomings have motivated researchers to explore reinforcement techniques aimed at improving the mechanical performance and durability of asphalt concrete.

Among various improvement strategies, fiber reinforcement has proven to be an effective method for enhancing the behavior of brittle and quasi-brittle materials. Extensive experimental and numerical investigations on fiber-reinforced cementitious and composite materials have shown that fibers significantly enhance strength, toughness, and post-cracking performance by bridging cracks and redistributing stresses in critical regions [1, 2]. The crack-bridging mechanism provided by fibers reduces stress localization and delays crack propagation, leading to improved structural integrity and energy absorption capacity.

The mechanical contribution of fibers strongly depends on their material properties and volume fraction. Steel fibers, owing to their high elastic modulus and tensile strength, are particularly effective in increasing stiffness and load-bearing capacity by forming efficient stress transfer bridges across cracks. In contrast, synthetic fibers such as polyacrylonitrile (PAN) fibers primarily improve toughness and deformation capacity, resulting in more ductile behavior and enhanced crack control. Similar distinctions between stiff and ductile reinforcement mechanisms have been reported in various composite and retrofitted structural systems [3, 4].

With the advancement of computational mechanics, the finite element method (FEM) has become a reliable tool for simulating the nonlinear behavior of reinforced materials. FEM enables detailed evaluation of stress distribution, damage evolution, and failure mechanisms that are difficult to observe experimentally. Previous studies have demonstrated that advanced constitutive models can accurately represent cracking and stiffness degradation in composite systems when properly calibrated [5, 6]. In this regard, the Concrete Damaged Plasticity (CDP) model implemented in ABAQUS has been widely adopted for modeling damage initiation and propagation in quasi-brittle materials, showing good agreement with experimental results.

Despite the extensive research on fiber-reinforced concrete and structural composites, numerical investigations focusing on fiber-reinforced asphalt concrete particularly comparing steel and macrosynthetic fibers remain limited. Moreover, the combined influence of fiber type and volume fraction on stress concentration, crack evolution, and load–displacement response has not been thoroughly investigated within a unified numerical framework. Addressing this research gap is essential for optimizing fiber-reinforced asphalt mixtures based on specific design objectives.

Among various modification techniques, fiber reinforcement has emerged as an effective approach to enhance the structural performance of asphalt mixtures. The incorporation of fibers into asphalt concrete, commonly referred to as fiber-reinforced asphalt concrete (FRAC), has been shown to significantly improve cracking resistance, toughness, fatigue life, and post-cracking behavior [7]. Fibers act as crack-bridging elements, restraining crack initiation and propagation while redistributing stresses over a wider area, thereby reducing stress concentration in critical regions.

Previous experimental studies have demonstrated that different fiber types can effectively enhance specific performance aspects of asphalt concrete. Steel fibers, due to their high elastic modulus and tensile strength, substantially improve load-bearing capacity and cracking resistance, particularly at low temperatures [8]. Similarly, carbon fibers and other high-strength fibers have been reported to enhance stiffness, fatigue resistance, and overall pavement performance [9]. Laboratory investigations further indicate that the reinforcing mechanisms of fibers depend strongly on fiber geometry, orientation, and volume fraction, which directly influence the stress transfer efficiency across cracks [10].

Environmental conditions such as temperature variations and moisture ingress also play a critical role in the performance of asphalt pavements. Studies on fiber-reinforced asphalt concrete under different environmental conditions have shown that fibers improve resistance to moisture damage and temperature-induced cracking by enhancing internal cohesion and energy dissipation capacity [11]. In addition, fiber-reinforced asphalt mixtures have demonstrated superior fatigue performance and long-term durability compared to conventional asphalt concrete, making them suitable for demanding applications such as airfields and heavy-duty pavements [12].

Recent advances in experimental techniques and material characterization have provided further insight into the fracture behavior of FRAC. Digital Image Correlation (DIC) and fracture mechanics-based studies have revealed that fiber reinforcement significantly increases fracture energy and dissipated creep strain energy, leading to more stable crack growth and enhanced toughness, especially at low temperatures [13]. Moreover, the effectiveness of fiber reinforcement is highly dependent on fiber length, distribution, and state within the asphalt matrix, highlighting the importance of optimizing fiber parameters for desired performance outcomes [14, 15].

Accordingly, the present study aims to numerically investigate the mechanical behavior of asphalt concrete reinforced with steel fibers and macrosynthetic PAN fibers at different volume fractions using the finite element method in ABAQUS. The Concrete Damaged Plasticity model is employed to simulate damage initiation and crack propagation. The numerical results are analyzed in terms of stress contours and load–displacement responses and are validated against experimental data reported in the literature (Gao et al., 2021)[16] to confirm the accuracy and reliability of the developed modeling approach.

The increasing traffic loads, severe temperature fluctuations, and fatigue phenomena in pavement layers are among the most significant challenges in road engineering. Asphalt concrete, as the primary material used in flexible pavement layers, exhibits viscoelastic behavior and is susceptible to early cracking under tensile stresses. To overcome this weakness, the use of fibers as mechanical reinforcement has gained significant attention in recent years.
Steel fibers, due to their high modulus of elasticity and tensile strength, enhance load-carrying capacity and initial strength; however, their non-uniform dispersion within the asphalt matrix is considered one of the main practical challenges. In contrast, macrosynthetic fibers (such as PAN or PVA),

which exhibit strong bonding and uniform distribution, contribute to increased toughness and post-cracking durability of asphalt concrete.

Although numerous experimental studies have been conducted on this subject, a deeper understanding of the internal mechanisms and the precise influence of fiber type and content requires advanced numerical analysis.

Several studies have investigated the effect of fibers on the mechanical performance of asphalt mixtures. Zhao et al. (2020) reported that incorporating steel fibers significantly increases compressive strength and load-bearing capacity of asphalt concrete[17]. Similarly, Gao et al. (2021) demonstrated that macrosynthetic fibers such as PAN, by improving the bridging mechanism in crack regions, lead to higher toughness, greater energy absorption, and enhanced fracture stability[16].

These results align with the objectives of the present research and justify the need for a comparative evaluation of steel and PAN fibers under identical conditions. Therefore, the main objective of this study is to develop an accurate finite element (FE) model in ABAQUS software to simulate the indirect tensile test (Brazilian test) of fiber-reinforced asphalt concrete and to evaluate the effect of fiber type and content on its strength and toughness.

2. Literature Review

In recent years, numerous studies have examined the mechanical behavior of fiber-reinforced asphalt concrete.

Gao et al. (2021), through a combination of experimental tests and finite element modeling, demonstrated that adding 0.3% PAN fibers led to an approximately 20% improvement in indirect tensile strength of asphalt concrete[16].

In the reference study by Gao et al. (2021) which was used for validation in the present research the mechanical behavior of fiber-reinforced asphalt concrete under indirect tensile loading was analyzed through both experimental and numerical approaches, and a close agreement between load–displacement curves was reported[16].

Babalola et al. (2021) evaluated the residual strength of concrete at elevated temperatures and found that the addition of fibers can effectively mitigate thermal damage and preserve post-strength toughness[18].

Abdallah et al. (2017) investigated the pull-out behavior of straight and hooked-end steel fibers, concluding that fiber end shape plays a critical role in mechanical interlocking and stress transfer mechanisms[19].

Zheng et al. (2013) examined the compressive and tensile properties of steel fiber–reinforced reactive powder concrete, finding that the addition of steel fibers significantly increased fracture resistance and initial stiffness[20].

Moghadam and Izadifard (2020) compared the effects of steel and glass fibers on the durability of concrete exposed to high temperatures, reporting that steel fibers offer superior thermal and mechanical performance[21].

Mezzal et al. (2021) studied the impact resistance and fracture energy of fiber-reinforced high-strength self-compacting concrete and found that the inclusion of discarded steel fibers markedly improved impact resistance and fracture toughness[22].

Despite these numerous studies, most previous research focused on only one type of fiber, and direct comparisons between steel and macrosynthetic fibers under identical conditions remain limited. Therefore, the present study aims to fill this gap by conducting a comprehensive numerical comparison between both fiber types within the same modeling framework.

2.1 Fiber-Reinforced Asphalt Concrete: Concept and Mechanisms

The concept of fiber-reinforced asphalt concrete (FRAC) has been extensively investigated as an effective approach to mitigate common pavement distresses such as cracking, rutting, and fatigue failure. Fibers embedded within the asphalt matrix act as reinforcing elements that enhance tensile resistance and inhibit crack initiation and propagation. According to the comprehensive review conducted by Abtahi et al. (2010)[7], fiber reinforcement improves asphalt concrete performance by increasing mixture cohesion, redistributing stresses, and enhancing post-cracking behavior. The crack-bridging effect of fibers plays a key role in reducing stress concentration at microcrack tips and delaying macrocrack development.

2.2 Effect of Fiber Type on Mechanical Performance

The reinforcing efficiency of FRAC strongly depends on fiber material properties, including elastic modulus, tensile strength, and surface characteristics. Carbon fibers, due to their high stiffness and strength, have been shown to significantly improve stiffness and fatigue resistance of asphalt concrete [9]. Similarly, steel fibers have been reported to substantially enhance cracking resistance and load-bearing capacity, particularly under low-temperature conditions where asphalt mixtures exhibit brittle behavior [8]. These fibers form strong stress-transfer bridges across cracks, resulting in increased fracture resistance and improved structural integrity.

In contrast, synthetic fibers, such as polymer-based fibers, primarily contribute to improving toughness and ductility rather than stiffness. Studies on mechanically fiber-reinforced asphalt concrete (M-FRAC) have demonstrated that synthetic fibers enhance deformation capacity and crack control by promoting more stable crack growth and higher energy absorption [14]. This distinction between high-modulus and low-modulus fibers highlights the importance of fiber selection based on the desired performance objective.

2.3 Influence of Fiber Content, Length, and Distribution

Several studies have emphasized that fiber volume fraction, length, and dispersion significantly influence the performance of FRAC. Lee et al. (2005)[10] reported that increasing fiber content enhances fatigue cracking resistance, although excessive fiber dosage may lead to workability issues and non-uniform fiber distribution. Noorvand et al. (2022)[15] investigated the effect of fiber length and identified an optimal range that maximizes mechanical performance while maintaining adequate mixture homogeneity. Random and uniform fiber distribution has been identified as a critical factor in achieving consistent mechanical enhancement and effective stress redistribution within the asphalt matrix.

2.4 Environmental Effects: Temperature and Moisture

The performance of asphalt concrete is highly sensitive to environmental conditions, particularly temperature variations and moisture exposure. Xu et al. (2010)[11] examined the behavior of FRAC under different temperature and water conditions and reported that fiber reinforcement improves resistance to moisture damage and thermal cracking. At low temperatures, fiber-reinforced mixtures exhibit higher fracture toughness and reduced crack susceptibility compared to conventional asphalt concrete. Experimental investigations using advanced techniques such as Digital Image Correlation (DIC) further confirmed that fibers significantly increase fracture energy and dissipated creep strain energy, leading to enhanced cracking resistance under thermal loading [13].

2.5 Fracture and Fatigue Behavior of FRAC

Fracture and fatigue performance are critical indicators of pavement durability. Multiple studies have shown that fiber reinforcement improves fatigue life by delaying crack initiation and slowing crack propagation under cyclic loading [10, 12]. In applications requiring high durability, such as airfields and heavy-duty pavements, FRAC has demonstrated superior long-term performance and reduced maintenance requirements compared to conventional asphalt mixtures [12]. These improvements are attributed to enhanced energy dissipation and stable post-cracking behavior induced by fiber reinforcement.

2.6 Numerical Modeling and Research Gaps

While extensive experimental research has been conducted on FRAC, numerical modeling studies capable of capturing stress distribution, crack evolution, and damage mechanisms remain relatively limited. Most existing studies focus on laboratory testing, with fewer investigations employing advanced finite element frameworks to simulate the nonlinear behavior of fiber-reinforced asphalt concrete. The lack of comprehensive numerical studies comparing different fiber types and volume fractions represents a notable research gap. Advanced constitutive models implemented within FEM platforms, such as ABAQUS, offer significant potential to address this limitation by providing detailed insights into damage initiation, crack propagation, and failure mechanisms.

Accordingly, there is a clear need for systematic numerical investigations that evaluate the influence of fiber type and content on the mechanical response of asphalt concrete. Such studies can complement experimental findings and support performance-based design of fiber-reinforced asphalt mixtures.

3. Methodology

In this study, ABAQUS/Standard software was employed to develop a three-dimensional finite element (FE) model of cylindrical asphalt concrete specimens.
Specimen dimensions: diameter = 101.6 mm; height = 63.5 mm.

Element types:

Matrix (Asphalt Concrete): 3D solid element with reduced integration, C3D8R
Fibers: Linear elastic beam elements

The asphalt matrix material model was defined based on experimental data as follows:

- Elastic modulus: 1200 MPa
- Poisson's ratio: 0.3
- Compressive strength: 2.54 MPa
- Constitutive model: Elasto-plastic with softening, using the Concrete Damaged Plasticity (CDP) model

Fiber properties:

- Steel fibers: E = 200 GPa
- PAN fibers: E = 17 GPa

Numerical modeling was performed in the ABAQUS/Standard software. Cylindrical specimens with a diameter of 101.6 mm and a height of 63.5 mm were modeled. The matrix and fiber were connected using the Tied constraint, and both the matrix and the fibers were modeled using C3D8R and Beam elements, respectively. The loading was displacement-controlled at a rate of 1 mm/min.
The elastic modulus of the matrix and the fibers were considered to be 1200 MPa for the matrix made of PAN and 17 GPa for the steel fibers200 GPa, respectively. The

nterfacebetween the fiber and matrix was assumed to be fully bonded.

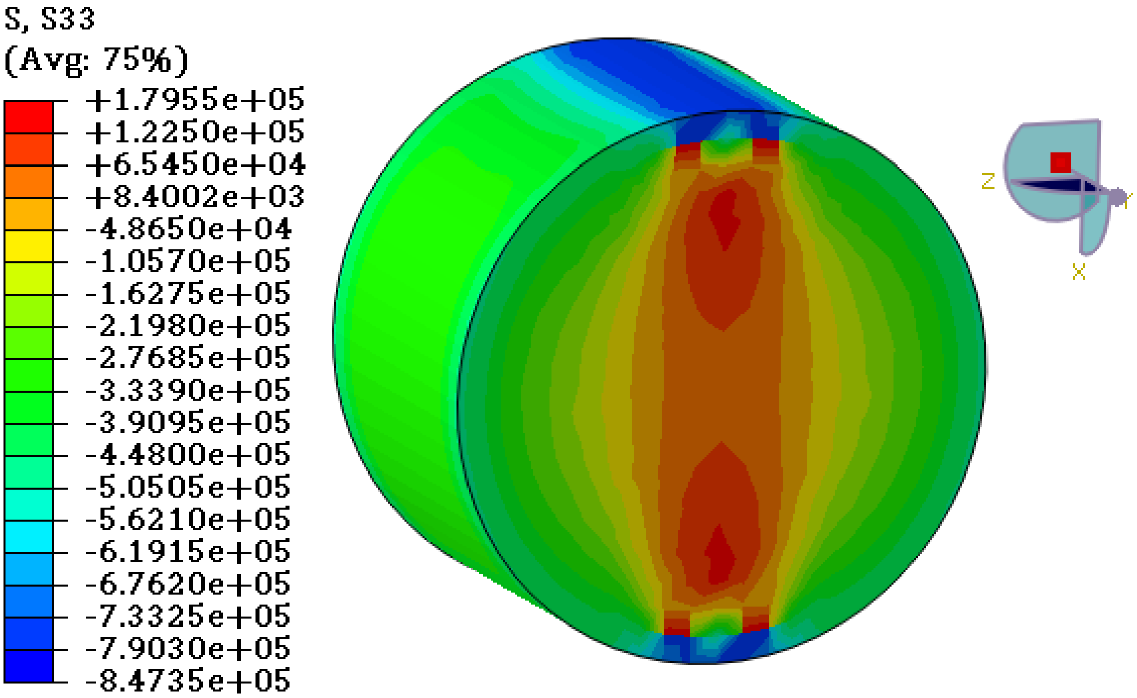

Figure 1. Schematic of the cylindrical specimen and how it is loaded in the compression test

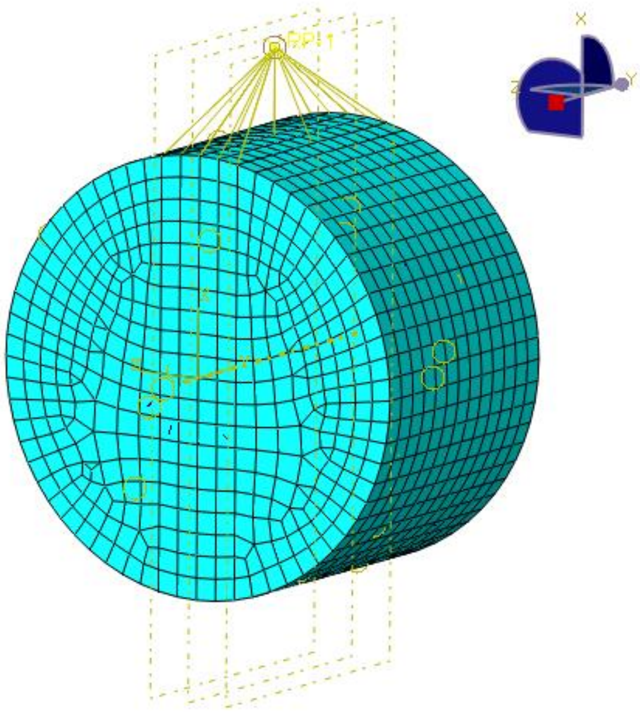

Figure2. 3D meshing of the sample (C3D8R) in ABAQUS software

Table 1. Mechanical properties of materials used in the numerical model

Material Type	Elastic Modulus (MPa)	Poisson's Ratio	Compressive Strength (MPa)	Behavior Type
Asphalt Matrix	1200	0.30	2.54	Elasto-plastic (CDP)
PAN Fibers	17000	0.30	—	Linear Elastic
Steel Fibers	200000	0.30	—	Linear Elastic

Table 1 shows that the main difference between steel fibers and pan fibers is in the modulus of elasticity.This difference causes a different performance in the strength of the material.

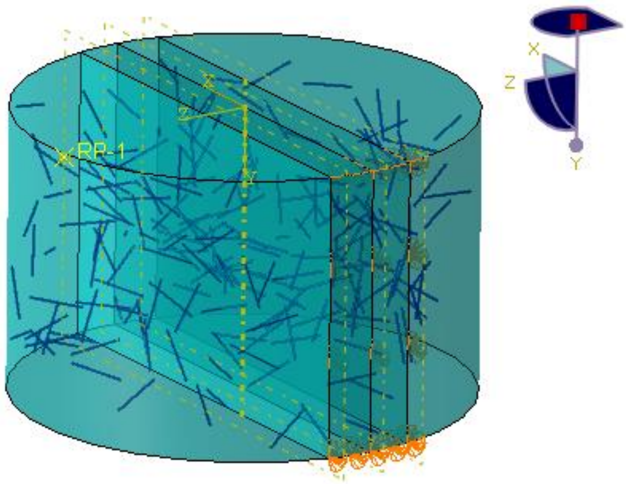

Figure 3(a).Random fiber distribution within the cylindrical model (sepcimens containing 2% fibers)

In samples containing 2% fibers, the fibers are mostly uniformly dispersed throughout the asphalt matrix, and sufficient spacing between fibers prevents any significant fiber–fiber stress interference. In this condition, fibers provide a limited but effective bridging mechanism, reducing stress concentration and improving post-cracking toughness without altering the matrix structure.

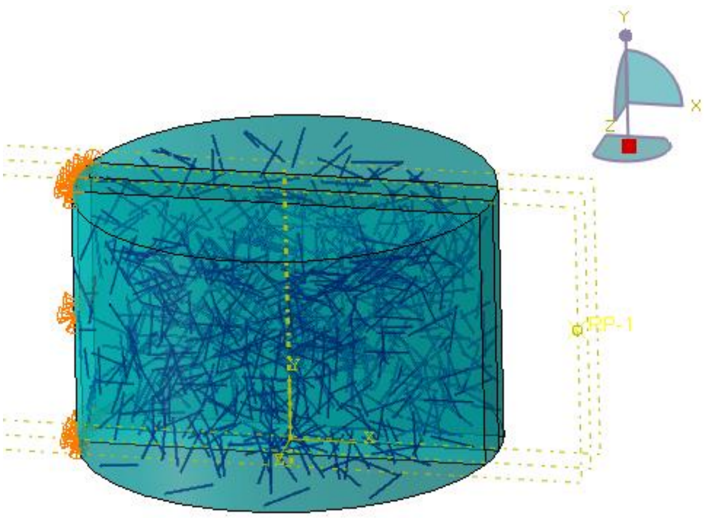

Figure 3(b).Random fiber distribution within the cylindrical model (sepcimens containing 4% fibers)

In samples containing 4% fibers, the fiber density and interaction increase noticeably, and regions of localized fiber clustering can be observed. This contributes to a greater capacity for stress transfer and thus an increase in ultimate strength, although it may also introduce local heterogeneity in the matrix. Therefore, while higher fiber content enhances crack control and structural resistance, ensuring uniform fiber dispersion becomes more critical at this level.

Table 2. Details of the numerical models considered

Model ID	Fiber Type	Fiber Volume Fraction (%)	Fiber Length (mm)	Performance Description
C0	—	0	—	Reference specimen without fibers
PAN0.2%	PAN	0.2	10	Increased post-crack energy absorption and toughness
PAN0.4%	PAN	0.4	10	Significant improvement in tensile behavior and stress distribution
ST0.2%	Steel	0.2	10	Increased initial strength and delayed crack initiation
ST0.4%	Steel	0.4	10	Highest strength and fracture stability

As shown in Table 2, increasing the fiber content, especially steel fibers, enhances ultimate and cracking strength. PAN fibers, though less effective in increasing peak strength, play a vital role in improving post-cracking behavior and toughness.

4. Research procedure

1. Geometric modeling in ABAQUS/CAE environment.
2. Random generation of fiber positions using internal Python code.
3. Application of boundary conditions and loading according to the Brazilian tensile test setup.
4. Nonlinear analysis using the Newton–Raphson method.
5. Model validation with the data from Gao et al. (2021).
6. Numerical comparison between all models (**C0, PAN0.2%, PAN0.4%, ST0.2%, ST0.4%**).

5. Results and Discussion

The results of the numerical simulations revealed that adding fibers to asphalt concrete significantly affects both load-bearing capacity and toughness of the material:

- Reference specimen (C0): Exhibited brittle behavior with a sudden failure occurring at the specimen’s center.

- PAN 0.2% fibers: Slight increase in ultimate strength (3.6%) and enhanced post-cracking toughness.
- Steel 0.2% fibers: 15.8% improvement in ultimate strength and a 1.3% rise in fracture resistance.
- PAN 0.4% fibers: 25.4% increase in ultimate strength and 30.2% improvement in fracture resistance.
- Steel 0.4% fibers: Highest improvement, with a 31.5% increase in ultimate strength and a 40.8% rise in fracture resistance.

Stress and strain contours showed that steel fibers reduced tensile stress concentration at the center of the specimen and promoted multiple, gradual crack propagation. In contrast, PAN fibers absorbed post-cracking energy, generating a pseudo-ductile response.

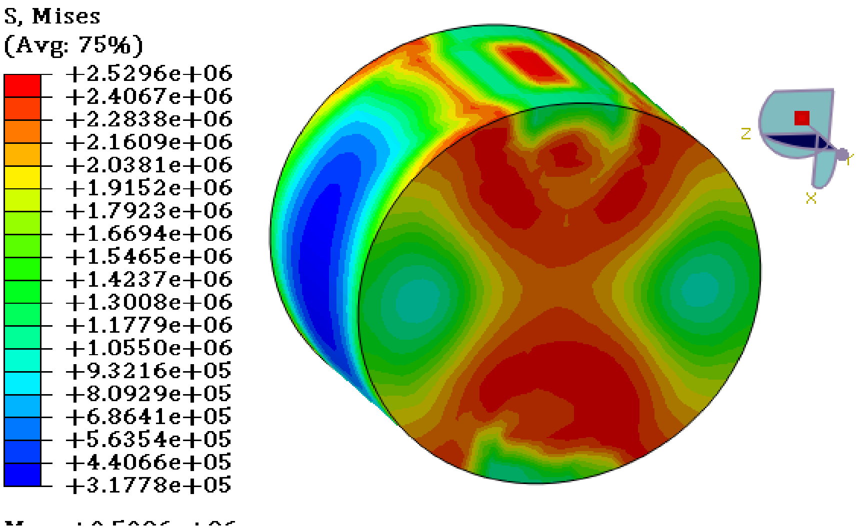

Figure 4. Stress contour of the reference model (C0)

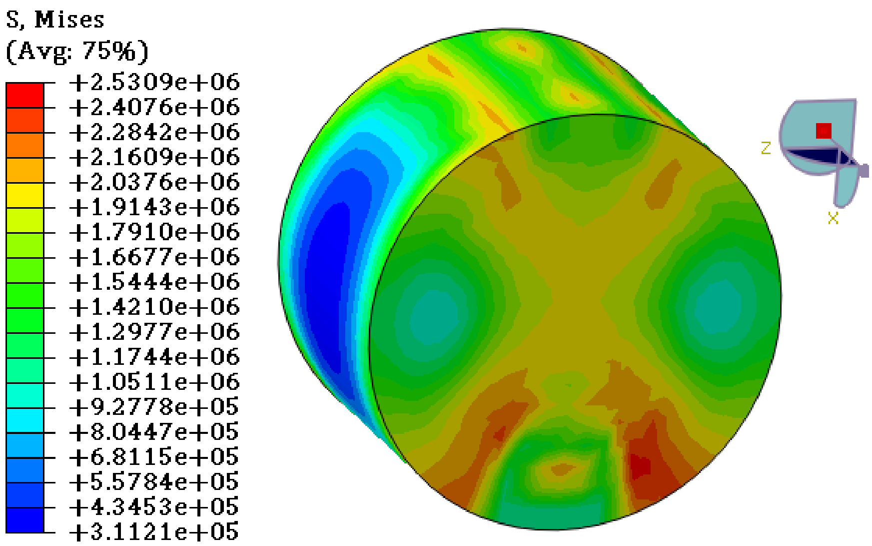

Figure 5. Stress contours of asphalt concrete containing 0.4% PAN fibers (PAN0.4%)

The increase in PAN concentration to 0.4% shows a significant reduction in the formation of micro and multiple cracks, which means that this phenomenon is more widespread, but the distributed stress intensity in the fibers has led to effective fracture control and improved durability of asphaltic materials. Ultimate strength has increased by about 25% and fracture toughness by about 30% compared to the reference sample. The cracks in this model exhibit behavior similar to the plastic region of the PAN0.2% model.

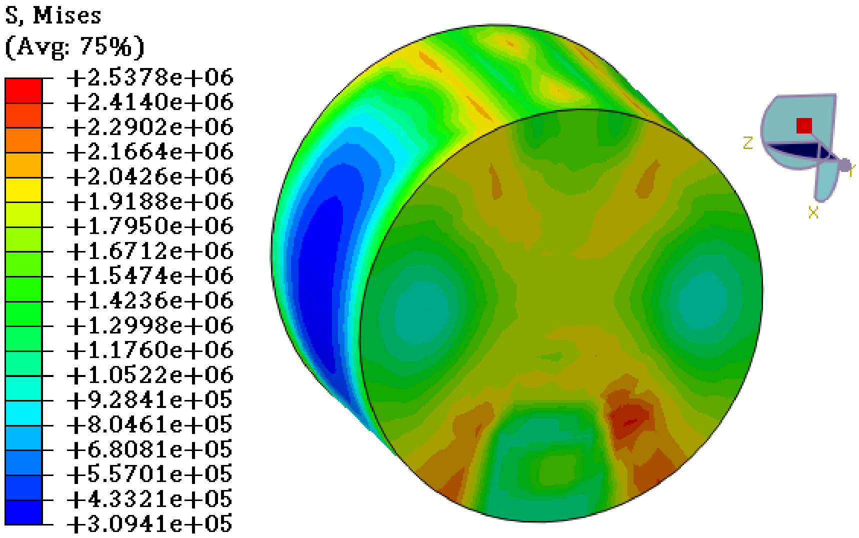

Figure 6. Stress contours and fracture pattern of asphalt concrete containing 0.4% steel fibers (ST0.4%)

An increase in the volume fraction of steel fibers to 0.4% leads to considerable changes in the mechanical behavior of the sample. In this model, irregular stress contours are evenly distributed throughout the specimen, indicating higher ductility and a more uniform distribution of fracture energy along multiple paths. The intensity of stress concentration has decreased, and the load‑deflection curve shows an enhancement of about.31.5% compared with the control sample. A 40.8% improvement in ultimate compressive strength and an increase in flexural strength compared with the reference model are observed. The steel fibers act as bridges across cracks, preventing sudden failure. This model demonstrates the most effective performance among all examined samples in terms of load‑bearing capacity and crack‑propagation control.

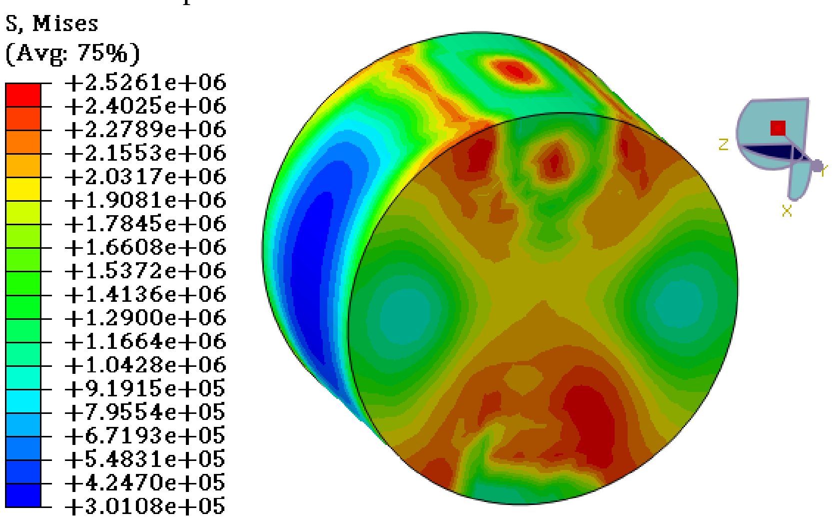

Figure 7. Stress contour and plastic strain distribution for asphalt concrete with 0.2% PAN fibers (PAN0.2%).

The analysis of the specimen containing 0.2% PAN macrosynthetic fibers revealed nuanced

changes in fracture response compared to the unreinforced concrete damaged (CD) model. The addition of this low fiber content resulted in limited alterations to the overall stress distribution pattern. The maximum stress magnitude remained largely similar to the reference model; however, the plastic zone surrounding the central crack initiation site exhibited an extension. Concurrently, a notable reduction in stress concentration was observed at the critical crack interface, primarily ascribed to the high flexibility of the PAN fibers and their enhanced energy absorption capacity post-cracking. Despite a measured reduction in apparent fracture resistance (approximately 7% compared to the CD specimen), the corresponding load-displacement curve indicated an increase in absorbed energy following the peak load. This is a strong indicator of improved post-cracking toughness and energy dissipation capability.

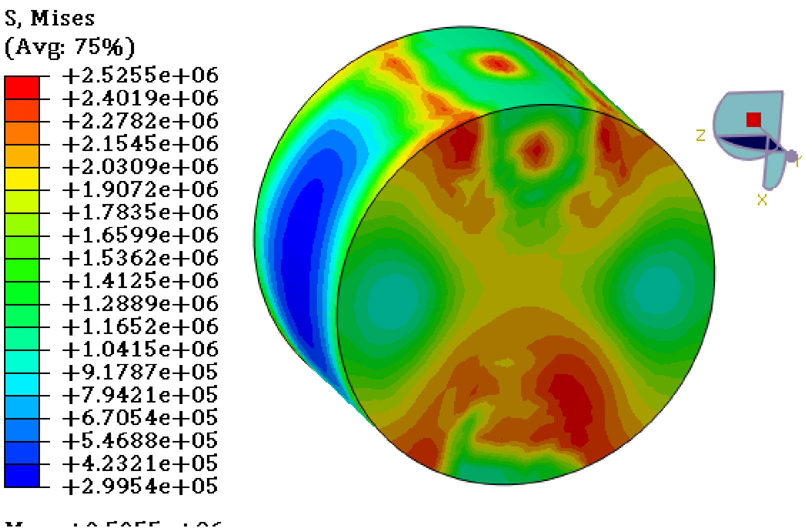

Figure 8. Stress contour and failure pattern of asphalt concrete with 0.2% steel fibers (ST0.2%).

6. Conclusion (General Summary)

This study employed a finite element approach based on the Concrete Damaged Plasticity (CDP) model to simulate the mechanical response of asphalt concrete reinforced with different types and contents of fibers.
The results demonstrated that incorporating fibers regardless of type significantly enhances mechanical strength, cracking resistance, and toughness.
However, the degree and mechanism of improvement depend strongly on fiber stiffness, bonding behavior, and distribution uniformity.
The overall accuracy of the developed numerical model was validated against reliable experimental data, showing a deviation of less than 5%.
This confirms the suitability of the CDP model for analyzing fiber-reinforced asphalt concrete in pavement and structural design applications.

Table 3. Comparison of Ultimate and Fracture Strength Among Models

Model	Ultimate Strength (N)	Fracture Strength (N)	Increase Compared to Reference (%)
C0	3005	2561	—
PAN0.2%	3113	2365	+3.6
PAN0.4%	3766	3334	+25.4
ST0.2%	3480	2593	+15.8
ST0.4%	3953	3610	+31.5

7. Validation

To evaluate the accuracy of the developed numerical model, validation was carried out using the experimental data of Gao et al. (2021)[16]. In this stage, a specimen containing 0.3% PAN fibers (6 mm in length) was selected. The numerical results obtained from ABAQUS were compared with the corresponding experimental data.
The comparison revealed that the difference between the maximum tensile stress predicted by the numerical model (0.612 MPa) and the experimental value (0.65 MPa) was less than 5%, indicating excellent model accuracy in predicting the mechanical behavior of fiber-reinforced asphalt concrete. Additionally, the load–displacement curve produced by the numerical simulation exhibited very close agreement with the experimental curve reported by Gao et al. (2021)[16], confirming the model's ability to capture nonlinear behavior and material softening.

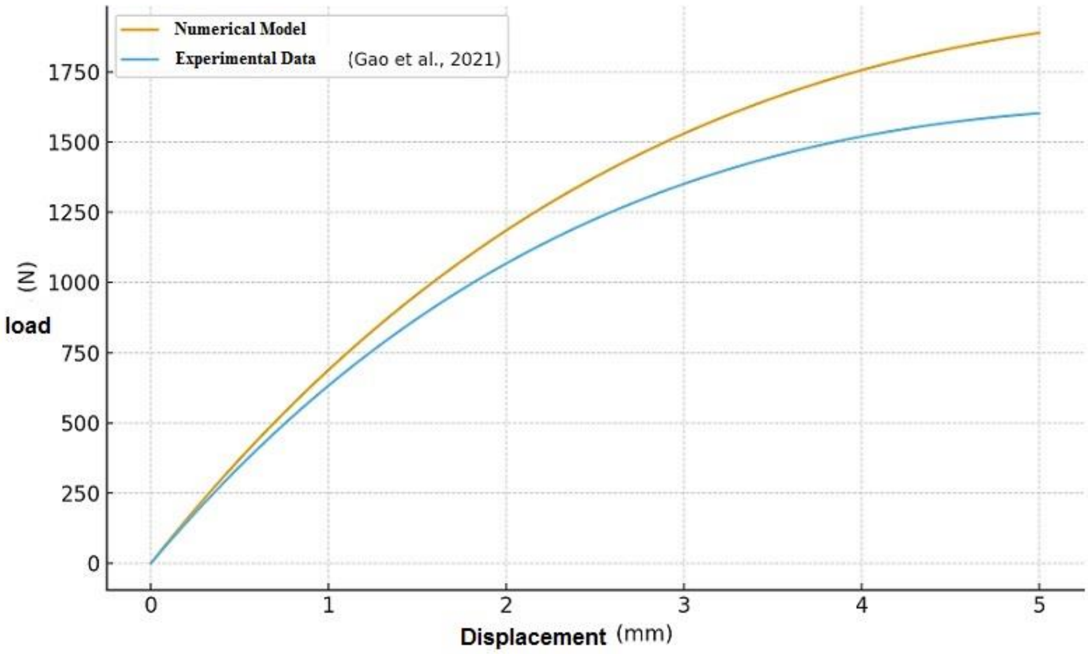

Figure 7. Comparison of the load displacement curve obtained from the numerical model with the experimental data .(Gao et al. 2021)[16]

As shown in Figure 7, the load–displacement curve obtained from the numerical simulation is in good agreement with the experimental .dataThe numerical model was able to reproduce the nonlinear behavior of the material, the load increase, and the peak point with less than 15% error. In both curves, the initial loading phase ,before cracking is approximately linearfollowed by a gradual decrease in load due to crack propagation. This behavior indicates that the Concrete Damaged Plasticity (CDP) model implemented in ABAQUS has adequate capability for simulating the behavior of damaged concrete.

8. Conclusion

In this research, the mechanical behavior of asphalt concrete reinforced with two types of fibers steel and macrosynthetic (PAN) at various volume fractions was simulated and analyzed using the Concrete Damaged Plasticity (CDP) model in ABAQUS. The findings of the numerical analysis and stress contour evaluation demonstrated that the inclusion of fibers, regardless of type, significantly enhances both the strength and toughness of asphalt concrete; however, the underlying mechanisms of improvement differ depending on the fiber type.

Steel fibers, due to their very high elastic modulus (≈200 GPa), substantially increased both initial and ultimate strength of the specimens. In the ST0.4% model, the stress distribution became multi-focal and less concentrated, reflecting the fiber's capability to act as stress-transfer bridges within the cracked region. This model exhibited the best structural performance, showing approximately 31.5% higher ultimate strength and 40% higher fracture resistance than the reference model.

In contrast, PAN fibers, while contributing less to the initial strength enhancement, improved internal adhesion and energy absorption capacity. They promoted a uniform stress distribution and prevented brittle fracture. In the PAN0.4% model, the plastic zone expanded with lower stress intensity, indicating ductile and tough post-cracking behavior. Thus, PAN fibers are more effective for long-term durability and crack stability under repeated loading or temperature variations.

The numerical model was validated against experimental data from Gao et al. (2021). The comparison between the numerical and experimental load–displacement curves showed an error below 5%, confirming that the CDP model is capable of accurately simulating the nonlinear damage behavior of fiber-reinforced asphalt concrete.

Table 4. Summary of Key Findings

Model ID	Key Performance Characteristic	Improvement (%)	Remark
ST0.4%	Highest load-bearing capacity and fracture resistance	+31.5	Best mechanical performance
PAN0.4%	Greatest energy absorption and crack stability	+25.4	Best ductile behavior
ST0.2%	Improved initial strength	+15.8	Effective stress bridging
PAN0.2%	Moderate energy absorption	+3.6	Slight increase in post-crack toughness
C0	—	—	Reference model (brittle failure)

8.1. Final Conclusions Final Conclusions

ST0.4% provided the best mechanical performance, showing superior strength and delayed crack initiation.

PAN0.4% offered the best ductility and fracture stability, making it ideal for durability-focused applications.

Fiber selection should be based on the design objective:

For high-load pavements such as airports and ports → Steel fibers are recommended.

For urban pavements or thermally sensitive environments → PAN fibers are more stable and cost-effective.

The validated numerical CDP model provides a reliable simulation framework for the design of fiber-reinforced asphalt pavements.

9. Novelty and Contributions

The present research introduces a comprehensive three-dimensional numerical model for fiber-reinforced asphalt concrete using the Concrete Damaged Plasticity (CDP) model in ABAQUS. Unlike previous studies that mainly focused on a single fiber type, this study provides a direct quantitative comparison between steel and macrosynthetic PAN fibers under identical modeling conditions. The major novelties and contributions are listed below:

- Development of a realistic 3D two-phase finite element model of fiber-reinforced asphalt concrete incorporating the CDP model in ABAQUS.
- Direct comparative evaluation between steel and macrosynthetic fibers under the same numerical framework.
- Validation of the numerical model using reliable experimental data (Gao et al., 2021) with an error margin below 5%.
- Simulation of random fiber distribution within the asphalt matrix to represent realistic material heterogeneity.
- Detailed analysis of bridging and crack-delay mechanisms for each fiber type.
- Provision of a practical numerical framework that can be employed for the design of fiber-reinforced asphalt pavements.

10.Refrence

[1] M. Eskandarinia, M. Esmailzade, A. Hojatkashani, A. Rahmani, and S. Jahandari, "Optimized alkali-activated slag-based concrete reinforced with recycled tire steel fiber," *Materials*, vol. 15, no. 19, p. 6623, 2022.https://doi.org/10.3390/ma15196623

[2] H. Nematian Jelodar, A. Hojatkashani, R. Madandoust, A. Akbarpour, and S. A. Hosseini, "Experimental investigation on the mechanical characteristics of cement-based mortar containing nano-silica, micro-silica, and PVA fiber," *Processes*, vol. 10, no. 9, p. 1814, 2022. https://doi.org/10.3390/pr10091814

[3] A. Hojatkashani and M. Kabir, "Experimental examination of CFRP strengthened RC beams under high cycle fatigue loading," *International Journal of Civil Engineering*, vol. 10, no. 4, pp. 291-300, 2012.

[4] V. Garmeh, A. Akbarpour, M. Adibramezani, A. H. Kashani, and M. Adibi, "Introducing and numerical study of an innovative rotational damper with replaceable hourglass steel pins," in *Structures*, 2021, vol. 33, pp. 2019-2035: Elsevier. https://doi.org/10.1016/j.istruc.2021.05.072

[5] M. ZAMAN KABIR and A. Hojatkashani, "A COMPARISON BETWEEN FINITE ELEMENT AND ANALYTICAL SOLUTIONS OF INTERFACIAL STRESS DISTRIBUTION IN A RC BEAM RETROFITTED WITH FRP COMPOSITES," *Amirkabir Journal of Science and Research*, vol. 39, no. 1, pp. 29-29, 2008.

[6] R. Hassani, A. Hojatkashani, and R. Basirat, "Nonlinear seismic analysis of ground structure to evaluate the capacity of a permanent tunnel lining," *Structural Engineering International*, vol. 34, no. 1, pp. 102-113, 2024. https://doi.org/10.1080/10168664.2022.2125485

[7] S. M. Abtahi, M. Sheikhzadeh, and S. M. Hejazi, "Fiber-reinforced asphalt-concrete–a review," *Construction and Building Materials*, vol. 24, no. 6, pp. 871-877, 2010. https://doi.org/10.1016/j.conbuildmat.2009.11.009

[8] P. Park, S. El-Tawil, S.-Y. Park, and A. E. Naaman, "Cracking resistance of fiber reinforced asphalt concrete at− 20 C," *Construction and Building Materials*, vol. 81, pp. 47-57, 2015. https://doi.org/10.1016/j.conbuildmat.2015.02.005

[9] S. G. Jahromi and A. Khodaii, "CARBON FIBER REINFORCED ASPHALT CONCRETE," *Arabian Journal for Science & Engineering (Springer Science & Business Media BV)*, vol. 33, 2008.

[10] S. J. Lee, J. P. Rust, H. Hamouda, Y. R. Kim, and R. H. Borden, "Fatigue cracking resistance of fiber-reinforced asphalt concrete," *Textile Research Journal*, vol. 75, no. 2, pp. 123-128, 2005. https://doi.org/10.1177/004051750507500206

[11] Q. Xu, H. Chen, and J. A. Prozzi, "Performance of fiber reinforced asphalt concrete under environmental temperature and water effects," *Construction and Building materials*, vol. 24, no. 10, pp. 2003-2010,

2010.https://doi.org/10.1016/j.conbuildmat.2010.03.012

[12] J. J. Stempihar, M. I. Souliman, and K. E. Kaloush, "Fiber-reinforced asphalt concrete as sustainable paving material for airfields," *Transportation research record*, vol. 2266, no. 1, pp. 60-68, 2012. https://doi.org/10.3141/2266-07

[13] Q. Guo, H. Wang, Y. Gao, Y. Jiao, F. Liu, and Z. Dong, "Investigation of the low-temperature properties and cracking resistance of fiber-reinforced asphalt concrete using the DIC technique," *Engineering Fracture Mechanics*, vol. 229, p. 106951, 2020. https://doi.org/10.1016/j.engfracmech.2020.106951

[14] H. Noorvand, R. Salim, J. Medina, J. Stempihar, and B. S. Underwood, "Effect of synthetic fiber state on mechanical performance of fiber reinforced asphalt concrete," *Transportation Research Record*, vol. 2672, no. 28, pp. 42-51, 2018. https://doi.org/10.1177/0361198118787975

[15] H. Noorvand, M. Mamlouk, and K. Kaloush, "Evaluation of optimum fiber length in fiber-reinforced asphalt concrete," *Journal of Materials in Civil Engineering*, vol. 34, no. 3, p. 04021494, 2022. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004128

[16] H. Gao, L. Zhang, D. Zhang, T. Ji, and J. Song, "Mechanical properties of fiber-reinforced asphalt concrete: Finite element simulation and experimental study," *e-Polymers*, vol. 21, no. 1, pp. 533-548, 2021.

[17] Y. Zhang, H. Peng, L. Gao, J. Wang, and X. Cai, "Effects of polymer latex and expansive agent on the resistance of cement asphalt pastes to sulfuric acid attacks," *Journal of Materials in Civil Engineering*, vol. 32, no. 6, p. 04020128, 2020. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003224

[18] O. Babalola, P. O. Awoyera, D.-H. Le, and L. B. Romero, "A review of residual strength properties of normal and high strength concrete exposed to elevated temperatures: Impact of materials modification on behaviour of concrete composite," *Construction and Building Materials*, vol. 296, p. 123448, 2021. https://doi.org/10.1016/j.conbuildmat.2021.123448

[19] S. Abdallah, M. Fan, and K. Cashell, "Pull-out behaviour of straight and hooked-end steel fibres under elevated temperatures," *Cement and Concrete Research*, vol. 95, pp. 132-140, 2017.https://doi.org/10.1016/j.cemconres.2017.02.010

[20] W. Zheng, B. Luo, and Y. Wang, "Compressive and tensile properties of reactive powder concrete with steel fibres at elevated temperatures," *Construction and Building Materials*, vol. 41, pp. 844-851, 2013.https://doi.org/10.1016/j.conbuildmat.2012.12.066

[21] M. A. Moghadam and R. A. Izadifard, "Effects of steel and glass fibers on mechanical and durability properties of concrete exposed to high temperatures," *Fire Safety Journal*, vol. 113, p. 102978, 2020.https://doi.org/10.1016/j.firesaf.2020.102978

[22] S. K. Mezzal, Z. Al-Azzawi, and K. B. Najim, "Effect of discarded steel fibers on impact resistance, flexural toughness and fracture energy of high-strength self-compacting concrete exposed to elevated temperatures," *Fire Safety Journal*, vol. 121, p. 103271, 2021. https://doi.org/10.1016/j.firesaf.2020.103271