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REVIEW

Experimental Study on the Influence of Date Palm Fibers Reinforced Bituminous Mixtures

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ABSTRACT

This study investigates the influence of date palm fibers (DPF) on the mechanical performance of bituminous mixtures using two experimental methodologies: the wet and dry processes. In the wet process, DPFs were pre-blended with bitumen at varying contents ranging from 1% to 5% by weight, prior to mixing with aggregates. The resulting mixtures were evaluated based on several key performance indicators, including Marshall stability, creep resistance, compactness, and water sensitivity. The inclusion of fibers generally enhanced mechanical properties, with optimal improvements observed at 2% to 4% fiber content. Notably, the mixture with 3% DPF content demonstrated a 35.7% increase in Marshall stability, while the lowest compactness reduction (−1.9%) occurred at 1% fiber addition. In the dry process, the effects of both fiber length (1 cm, 3 cm, and 5 cm) and fiber content (0.1% to 0.5%) were examined, focusing specifically on rutting and creep resistance. The results showed that 3 cm fibers significantly improved rutting resistance, whereas the 0.1% fiber content yielded the highest enhancement in creep resistance. However, no clear correlation was established between the two performance metrics, suggesting that the mechanical response is highly

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deformation-dependent. Overall, the addition of DPF contributed to improved durability, strength, and resistance to deformation in asphalt mixtures. The findings underscore the potential of date palm fibers as a sustainable, low-cost, and environmentally friendly additive in pavement engineering, particularly in regions where palm waste is readily available and underutilized.

Keywords: Date Palm Fibers; Creep Behavior; Rutting Resistance; Oedometric Apparatus; Sustainable Development

1. Introduction

Bituminous mixtures serve as the backbone of flexible pavement construction due to their durability, flexibility, and cost-effectiveness [1]. However, with increasing traffic loads and environmental stressors, there is a growing need to enhance their mechanical performance, particularly in terms of resistance to creep and rutting [2]. These permanent deformations, caused by long-term traffic and thermal loading, significantly reduce pavement lifespan, necessitating the development of more robust asphalt composites [3,4].

In response, researchers have extensively explored the use of modifiers to enhance the performance of bituminous mixtures. Among these, natural fibers have attracted considerable attention for their renewability, environmental benefits, and ability to alter the rheological and mechanical properties of asphalt binders [5]. Natural fibers such as cellulose, rice husk, and polypropylene have demonstrated promising improvements in stiffness, fatigue resistance, and rutting performance [6,7]. Date palm fibers (DPF), in particular, are abundant in arid and semi-arid regions and represent a valuable agricultural byproduct with potential as an asphalt modifier [8,9]. Their low cost, high availability, and fibrous structure make them an environmentally and economically attractive alternative to synthetic fibers.

Valorizing agricultural waste like DPF is a key component of sustainable infrastructure development. In regions where palm cultivation is prevalent, large quantities of biomass waste— leaves, stems, and fibers—are typically discarded or burned, contributing to pollution and resource inefficiency [10]. Incorporating such fibers into bituminous mixtures can simultaneously enhance pavement performance and reduce environmental impact [11,12]. Prior studies on agricultural waste in cementitious and composite materials have shown similar benefits in terms of mechanical and environmental performance [13,14].

The reinforcement of asphalt with fibers has been shown to improve resistance to fatigue, thermal cracking, moisture damage, and permanent deformation [15,16]. Polypropylene fibers, for instance, reduce the creep rate under static loads, while cellulose fibers improve stiffness and fatigue life [17]. These mechanical improvements are governed by several parameters, including fiber type, length, and concentration [18]. Some studies indicate that longer fibers improve rutting resistance but may compromise creep performance. Moreover, excessive fiber content can disrupt matrix cohesion and reduce workability [19].

Recent advances in composite engineering have further emphasized the relevance of fiber geometry, treatment, and hybrid filler integration on the mechanical and vibrational behavior of materials [20–23]. For example, alkali treatment has been shown to significantly alter the buckling and mechanical behavior of fiber-reinforced composites [20]. At the same time, filler-laminated plates fabricated with natural and industrial fibers exhibit enhanced strength and vibrational characteristics [21,22].

Given these complexities, this study investigates the specific effects of DPF on both creep and rutting resistance in asphalt mixtures. By examining mixtures with varying fiber lengths (1 cm, 3 cm, and 5 cm) and concentrations (0.1%, 0.3%, and 0.5%), we aim to uncover the relationships between fiber parameters and mechanical performance. Understanding these interactions is crucial for optimizing mix design in pavement applications [23–25].

An experimental approach based on both dry and wet fiber incorporation methods is adopted. Mechanical performance is assessed through Marshall stability, static creep resistance, rutting, and water sensitivity tests. A total of nine fiber-reinforced and one control mixture is prepared to evaluate the combined influence of fiber length, content, and incorporation technique on the durability and deformation resistance of asphalt mixtures.

This study is distinguished by its comparative analysis of wet/dry processes and unique focus on date palm fibers (DPF), an underutilized resource in bituminous mixtures. Unlike existing studies on synthetic fibers, this research quantifies the simultaneous impact of DPF length (1–5 cm) and dosage (0.1–5%), addressing a gap in the literature.

By addressing both performance enhancement and waste valorization, this study contributes to the development of sustainable and high-performance asphalt composites. The results are expected to inform the design of eco-efficient pavements that meet the increasing demands of modern infrastructure development.

2. Materials and methods

2.1. Asphalt

The physical properties of the binder used in this study are presented in **Table 1**. The binder is a 35/50 penetration grade pure bitumen [26], which was sourced from Naftal Company, a leading supplier of petroleum-based products. This type of bitumen is widely utilized in road construction across Algeria due to its optimal balance of viscosity, durability, and adhesion properties, making it well-suited for pavement applications.

2.2. Aggregates

The aggregates used in this study consist of granular fractions commonly utilized in Algeria for the production of bituminous mixtures intended for wearing courses. These aggregates were sourced from the Ain Touta quarry in Batna, located in the northern region of Algeria. Their physical and mechanical properties, detailed in **Table 2**, fully conform to Algerian specifications [26], ensuring their suitability for use in asphalt mixtures. The selection of these aggregates is based on their high durability, strength, and compatibility with bituminous binders, which are essential for achieving long-lasting and resistant pavement surfaces.

Table 1. Physical properties of asphalt.

Test Type	Standard	Result	AlgerianSpecifications
Penetration at 25 °C (1/10mm) Softening	EN1426	42.3	40–50
Point Ring and Ball “SPRB” (°C)	EN1427	54.50	47–61
Ductility at 25 °C (cm)	EN13589	100	≥ 60

Table 2. Characteristics of the aggregates – classes 0/3, 3/8, 8/15.

	Volume Mass (t/m^3)	LA	MDE
0/3	2.67	-	-
3/8	2.68	21.40	8.00
8/15	2.68	24.92	6.74
Algerian Specifications		≤ 25%	≤ 20%

2.3. Date Palm Fiber

Date palm fibers used in this study were extracted from palm tree waste collected in Tamanrasset, located in the southern region of Algeria. To ensure their suitability for incorporation into bituminous mixtures, a systematic preparation procedure was followed.

First, the palm fiber strips were immersed in water to facilitate defibration, allowing the fibers to separate more efficiently. The individual fibers were then subjected to a thorough washing process to eliminate impurities and remove the lignin layer surrounding the fibers, which can hinder their adhesion to the bituminous matrix. Commercial household bleach (sodium hypochlorite solution at ~5%) was used in small quantities—just a few drops diluted in water— during the washing stage of the date palm fiber preparation process. The purpose of this bleaching step was not to chemically modify the fibers, but rather to assist in the removal of surface impurities, including dust, oils, and lignin residues, thereby improving fiber cleanliness and promoting better adhesion with the bituminous matrix. Unlike conventional alkali treatment (e.g., NaOH immersion), which aggressively modifies the fiber’s surface structure and chemical composition, the mild bleaching applied here was intended as a preliminary cleaning step, preserving the fibers’ natural integrity while enhancing surface compatibility.

Following the cleaning process, the fiber selection was carried out based on size and mechanical strength. Fibers with low strength and small dimensions were discarded to minimize variability in the study. The final fiber lengths chosen for the experimental program were 1 cm, 3 cm, and 5 cm, with careful efforts made to maintain a relatively uniform diameter along the useful section. Finally, the selected fibers were precisely cut to the required lengths using a razor blade, ensuring consistency across all samples.

Fiber lengths (1, 3, 5 cm) were selected based on preliminary tests showing that <3cm improves bitumen-fiber adhesion, while >3cm reduces homogeneity [27]. Dosages (0.1–5%) cover typical ranges for natural fiber studies [28].

2.4. Material Preparation

The studied formulation is based on a semi-coarse asphalt concrete (SCAC) 0/14, composed of granular classes 0/3, 3/8, and 8/15, and a 40/50 grade bitumen as the binder. This type of bituminous concrete is commonly used for road surfacing due to its durability and mechanical performance.

The optimum binder content (OBC) of the mixtures was determined using the Marshall and Duriez tests, ensuring an optimal balance between strength, durability, and workability [29,30]. For the reference mixture, the OBC was found to be 5.59%. The grading curve of the reference asphalt mix is illustrated in **Figure 1**, showing a distribution that complies with the standardized grading requirements for this type of asphalt concrete [26].

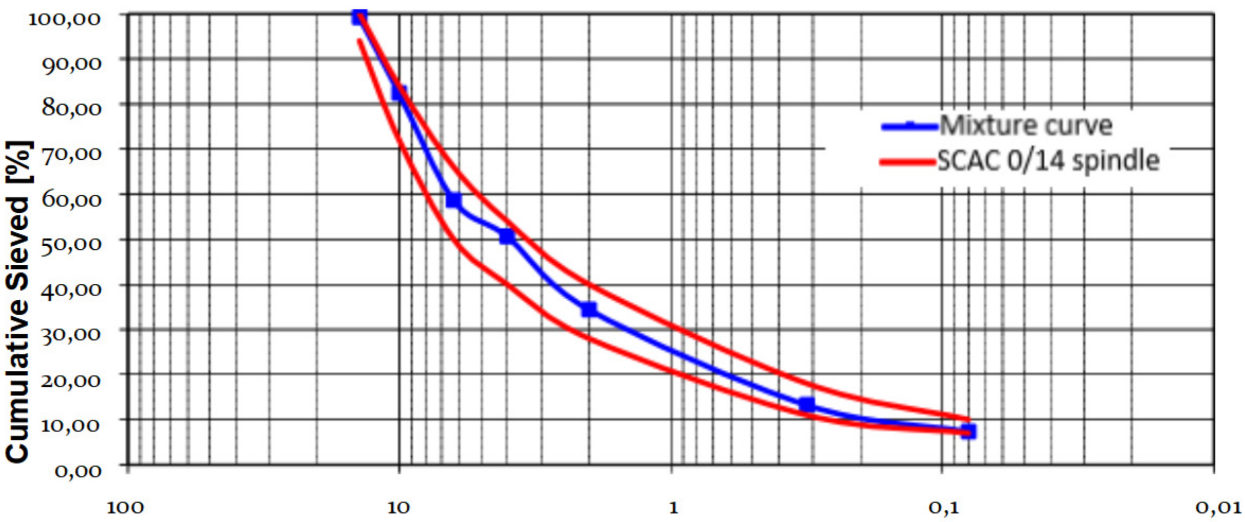

Figure 1. Grading curve of the reference asphalt.

The experimental program involved the use of date palm fibers (DPFs) incorporated into bituminous mixtures using two distinct preparation methods: the wet process and the dry process. In the wet process, DPFs were first blended with heated bitumen to ensure homogeneous dispersion before being mixed with aggregates. This approach focused solely on varying fiber content, leading to the preparation of five reinforced mixtures with 1%, 2%, 3%, 4%, and 5% fiber by weight of bitumen, alongside a control mix without fibers. In the dry process, fibers were introduced directly with the aggregates prior to bitumen addition, allowing the assessment of two parameters: fiber length (1 cm, 3 cm, and 5 cm) and fiber content (0.1%, 0.3%, and 0.5%). This resulted in nine different reinforced mixtures, in addition to a control mixture. For all mixes, conventional aggregates and 60/70 penetration-grade bitumen were used, while date palm fibers were dried, cleaned, and manually cut to the desired lengths before incorporation. The prepared mixtures were then subjected to various mechanical tests to evaluate their performance under different loading conditions.

2.5. Experimental Design

The experimental campaign was designed to investigate the influence of plant-based fibers on the mechanical properties of bituminous mixtures, particularly their resistance to permanent deformation. This study aims to assess whether the addition of plant-based fibers can enhance the overall performance and durability of asphalt mixtures, making them more resistant to the stresses induced by traffic loads and environmental conditions. However, first, we will analyze the influence of date palm fibers on the mechanical performance of bituminous concrete, focusing on Marshall stability, creep, and water resistance.

Also, creep and rutting tests were conducted, providing valuable insights into the material's ability to withstand long-term deformation under repeated loading [31,32].

The research was carried out in two main phases. In the first phase, a control mix was formulated, and its key physical and mechanical properties were established to serve as a benchmark for comparison. Once the control mix was characterized, the second phase involved modifying the mixture by incorporating plant-based fibers using the wet and dry process.

The wet process was employed, where date palm fibers were pre-mixed with bitumen before blending with aggregates. This study focused on a single variable: fiber content, preparing five fiber-reinforced mixtures (1%, 2%, 3%, 4%, and 5%), alongside a control mixture (0%) (**Table 3**). The mixtures were evaluated for Marshall stability, Marshall creep resistance, compactness, and water sensitivity.

Table 3. The amount of fibers added for each dosage (wet process).

Fibers (%)	1	2	3	4	5
Weight (g)	12	24	36	48	60

In the second experiment, two primary variables were considered: fiber length and fiber concentration. Three different fiber lengths were selected: 1 cm, 3 cm, and 5 cm, allowing for an assessment of how varying fiber dimensions influence the mechanical behavior of the asphalt mix (**Table 4**). Additionally, three fiber concentrations were chosen: 0.1%, 0.3%, and 0.5% of the total mass of the mixture (**Table 5**). By systematically combining these three lengths with the three concentration levels, a total of nine (09) different fiber-reinforced mixtures were formulated and prepared for testing. The detailed compositions of these mixtures are presented in **Tables 3** and **4**.

Table 4. The mixtures for different lengths and percentages of fibers (dry process).

Mixtures	1 cm			3 cm			5 cm		
	0.1%	0.3%	0.5%	0.1%	0.3%	0.5%	0.1%	0.3%	0.5%

Table 5. The amount of fibers added for each dosage (dry process).

Fibers (%)	0.1	0.3	0.5
Weight (g)	3.6	10.8	18

This comprehensive experimental design enables a thorough evaluation of the potential benefits and limitations of incorporating plant-based fibers in asphalt mixtures, providing a basis for optimizing their usage in road construction applications.

2.5.1. Uniaxial Static Creep Test

The device used is an apparatus proposed by LEEGO (Laboratory of Environment, Water, Geomechanics, and Structures) within the Civil Engineering Faculty of USTHB (University of Science and Technology Houari Boumediene). It is typically used for measuring soil consolidation and is of the oedometer type.

A galvanized metal water tank is fixed onto the lower platform of this device. This tank is connected, through special piping, to a water bath equipped with a high-pressure hydraulic pump. The water bath, the hydraulic pump, and the water tank together form a closed circuit that maintains a constant water level and temperature in the tank during the test (**Figure 2**).

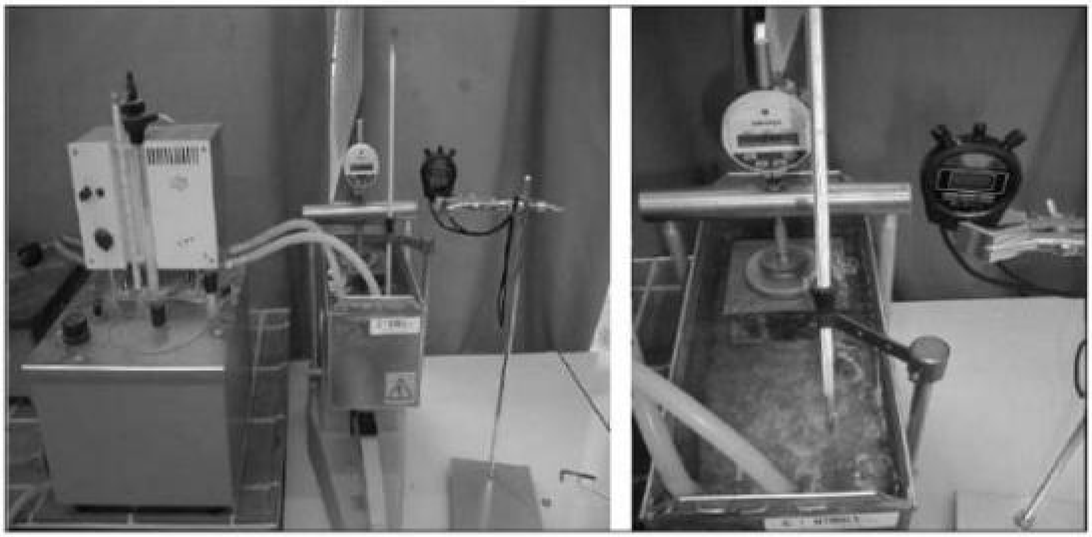

Figure 2. Equipment developed in the laboratory for testing.

The specimen is loaded using weights through a lever system. The load is transmitted to the specimen via a screw jack incorporated into the loading frame. One end of this jack is shaped like a hemisphere to fit into a recess on the surface of a disc placed on a perforated metal plate above the specimen. The other end operates the stem of a dial gauge, allowing it to be reset to zero (**Figure 2**). The 10 kg load at 60 °C follows EN 12697-46 to simulate Algerian pavement service conditions [26].

To prevent the sample from moving while the weights are being placed, another screw jack is incorporated at the base of the machine to support the lever temporarily. A special loading device ensures a secure setup at the beginning of the experiment. Two perforated and grooved metal plates distribute the applied load evenly across the entire surface of the specimen and allow the thermostated water to flow towards the loaded surfaces (**Figures 3** and **4**).

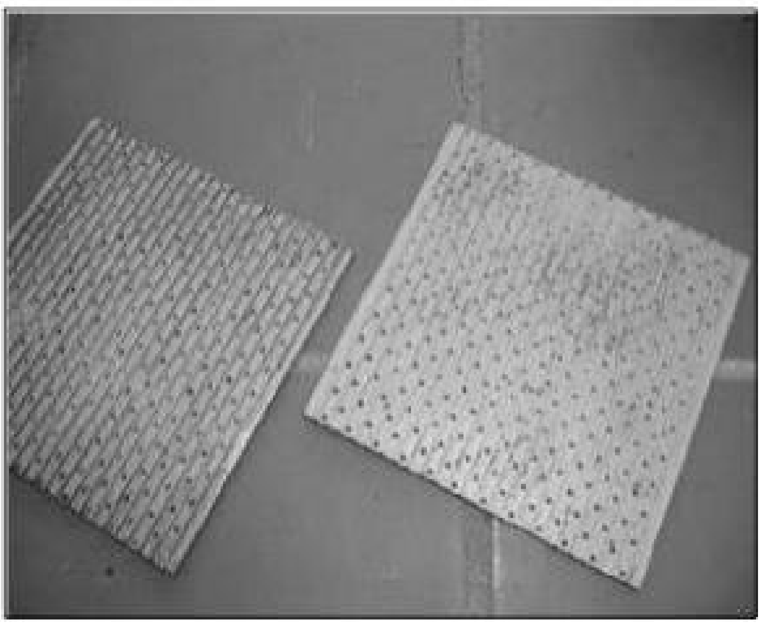

Figure 3. Porous metal plates.

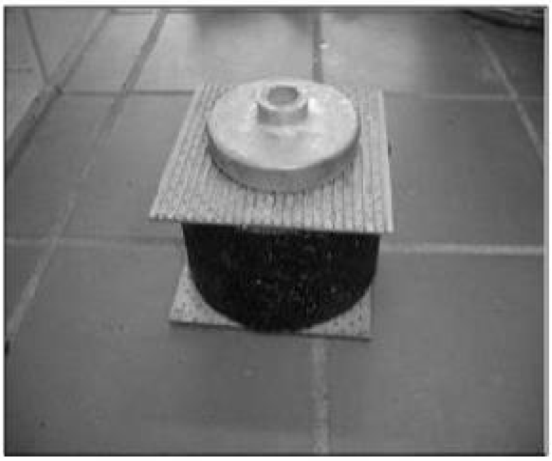

Figure 4. Position of the specimen between two metal plates, topped with a centrally recessed disc.

The relative displacement of the two plates during the test is indicated by a dial gauge positioned along the axis of the specimen.

Equation (1) used to determine the stress applied and the loaded surface of the specimen is as follows:

$$\sigma_0 = \frac{113.3M}{S} \quad (1)$$

Where:

- σ_0: Compressive stress applied to the specimen.
- **M**: Mass used.
- **S**: Loaded surface of the specimen.

2.5.2. Rutting Test

The rutting tests were conducted at the EPTRC (Public Roadworks Company) laboratory in Berrouaghia, Médéa province. These tests allowed us to evaluate five (05) different mixtures: (control; 1 cm 0.3%; 3 cm 0.1%; 3 cm 0.3%; and 5 cm 0.3%).

The repeated passage of a wheel equipped with a pneumatic tire applies a vertical load to a rutting test apparatus, which consists of a rolling load applied to a specimen fixed on a table (**Figure 5**). The wheel moves back and forth over the table, while a monitoring system measures the rate at which a rut forms on the specimen's surface. The vertical clearance in the rolling load mechanism must be less than 0.25 mm.

Figure 5. Compaction equipment according to EN 12697-33.

The apparatus must include:

- A wheel equipped with a treadless 400 × 8 pneumatic tire, with a track width of 80 ± 5 mm. The tire pressure must be 600 ± 30 kPa at the start of the test.
- A sample table capable of securely holding a laboratory-prepared plate.
- A mold with internal dimensions of 500 × 180 × 50 mm, with a tolerance of ± 2 mm, able to withstand the test conditions without warping.

A cold conditioning phase is required before starting the test, ensuring that the chamber is maintained at 25 °C. The machine then operates until the specimen has undergone 100 load cycles.

Calculation and Expression of Results

The percentage of measured rut depth, P_i, is calculated for each set of measurements using

15 local deformation values (m_{ij}) and the specimen thickness (h), according to the following Equation (2):

$P_i = \sum j = 115m_{ij} \times 100$P_i = \frac{\sum_{j=1}^{15} m_{ij}}{h} \times 100 (2)

Where:

P_i = Percentage of rut depth

m_{ij} = Local deformation value at measurement point j

h = Initial thickness of the specimen

This calculation provides an accurate assessment of the rutting resistance of the tested bituminous mixture.

3. Results and Discussion

3.1. Evolution of Marshall Stability

We aim to investigate the influence of fiber content on the Marshall stability of asphalt mixtures. **Figure 6** illustrates the results found.

The results indicate that modified bituminous concretes exhibit improved stability compared to the reference asphalt mix. This enhancement suggests that the incorporation of fibers contributes positively to the overall mechanical performance of the asphalt, particularly in terms of load-bearing capacity and resistance to deformation under applied stress.

A more detailed analysis of the stability variations as a function of fiber content reveals a nonlinear trend. Initially, the stability increases with fiber addition, reaching its peak at a fiber content of 3%. This suggests that up to this concentration, the fibers are well-dispersed within the mixture, effectively reinforcing the asphalt matrix and improving load transfer mechanisms. The presence of fibers likely enhances the interlocking between aggregates, reduces internal movement, and strengthens the cohesion of the mixture, thereby leading to a higher resistance to mechanical stresses.

However, beyond this optimum fiber concentration (3%), a decline in stability is observed.

Despite this reduction, the stability values remain higher than those of the control mix, indicating that fiber inclusion continues to provide reinforcement benefits. The decrease in stability at higher fiber contents (above 3%) could be attributed to fiber agglomeration and non-uniform distribution within the mix. The stability reduction beyond 3% correlates with increased void content (+ 12% at 5% fibers), confirming the agglomeration observed microscopically. Excessive fibers may create weak points by forming clusters that hinder proper bitumen coating and reduce the overall compactness of the mixture. This phenomenon could lead to a slight deterioration in mechanical performance despite the continued presence of reinforcing fibers.

These findings are consistent with previous studies on fiber-reinforced asphalt mixtures, which also report an optimum fiber content beyond which performance starts to decline. The results emphasize the importance of selecting an appropriate fiber dosage to maximize the benefits while avoiding potential negative effects such as fiber clumping, reduced workability, and increased void content.

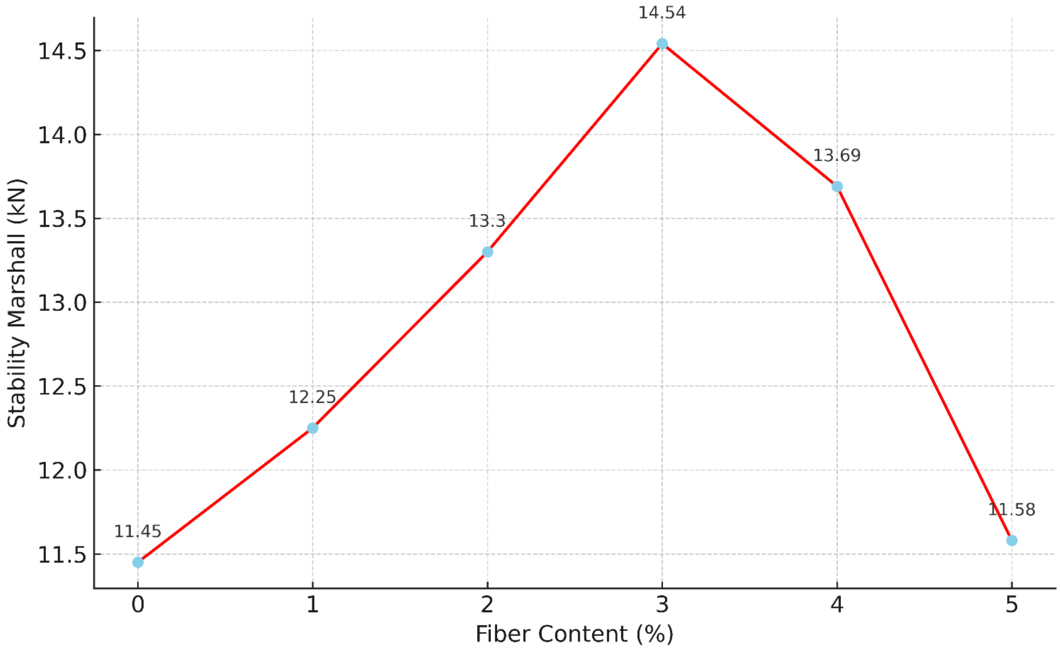

Figure 6. Evolution of Marshall stability with fiber content.

3.2. Evolution of Marshall Creep

We aim to investigate the influence of fiber content on the Marshall creep of asphalt mixtures (**Figure 7**).

The results presented in **Figure 7** indicate that the creep deformation of the asphalt mix increases with fiber content, reaching a maximum value of 4.77 mm at a fiber concentration of 3%, before gradually decreasing at higher fiber contents. Despite this reduction beyond 3%, the creep values remain higher than those of the control mix, suggesting that fiber incorporation influences the deformation behavior of the asphalt mixture.

The observed initial increase in creep with fiber addition can be attributed to the interaction between the fibers and the bituminous matrix. At lower fiber concentrations, fibers may act as stress concentrators, altering the internal structure of the mixture and slightly reducing its rigidity. This could lead to increased susceptibility to deformation under loading conditions. Additionally, fibers may introduce a slight increase in air voids within the mixture, potentially affecting the overall structural cohesion.

However, at a 3% fiber content, the material reaches its maximum creep value, indicating that the fibers have significantly influenced the viscoelastic behavior of the mix. This suggests that at this concentration, the fiber distribution within the bituminous matrix creates a structure that allows greater deformation while still maintaining internal cohesion. The creep resistance might be compromised at this stage due to a possible reduction in bitumen-fiber interaction efficiency or the formation of weak zones within the mixture.

Beyond the 3% threshold, a decrease in creep deformation is observed. This reduction may be explained by a more effective fiber network formation, which contributes to load transfer and better reinforcement of the mixture. At higher fiber concentrations, fibers are more uniformly distributed, leading to enhanced interlocking and a strengthening effect within the asphalt structure. This improvement counteracts excessive deformation, reducing the creep tendency. However, despite this reduction, the creep values remain above those of the control mix, indicating that fiber-modified asphalt mixtures retain higher flexibility compared to conventional mixtures.

In conclusion, this study confirms that fiber incorporation influences the creep resistance of asphalt mixtures, with 3% fiber content being the critical point where maximum deformation occurs. Further research could focus on evaluating the long-term performance of fiber-reinforced mixtures under real traffic conditions and exploring additional factors such as fiber type, dispersion techniques, and environmental influences to optimize their use in pavement applications.

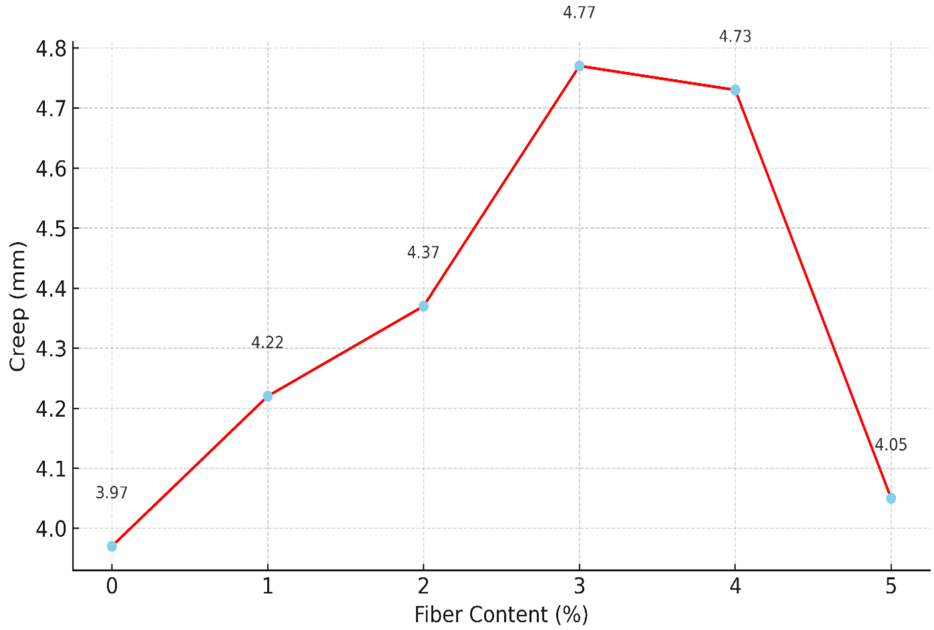

Figure 7. Evolution of Marshall creep with fiber content.

3.3. Evolution of the Marshall Quotient

The Marshall Quotient (MQ) is the ratio between stability and creep, representing the performance of the specimen. The MQ values were calculated to evaluate the resistance of the modified asphalt specimens. A higher quotient value indicates that the mixtures are more resistant to permanent deformation. The evolution of the quotient as a function of fiber content is presented in **Figure 8**.

The analysis of the Marshall Quotient (MQ) evolution as a function of fiber content provides valuable insights into the mechanical performance of fiber-reinforced asphalt mixtures. The results indicate that the 3% fiber mixture exhibits both the highest stability and the highest MQ, despite also having the maximum creep deformation. This suggests that at this specific fiber content, the reinforcement effect of the fibers is optimized, leading to a significant improvement in the mixture's resistance to permanent deformation while still allowing some degree of flexibility.

A closer examination of the trends reveals that while the other fiber-reinforced mixtures exhibit lower MQ values compared to the 3% fiber mixture, they still demonstrate higher resistance to deformation than the control mix. This indicates that fiber incorporation generally enhances the performance of the asphalt mixture by improving the balance between stability and flexibility. However, an exception is observed in the case of the 5% fiber content mixture, which shows a lower MQ than the control mix, suggesting that excessive fiber content may have adverse effects on the mechanical properties of the mixture.

The observed decrease in MQ at higher fiber concentrations (above 3%) could be attributed to fiber agglomeration, which may lead to heterogeneous distribution within the asphalt matrix. This clustering effect could create weak points in the mixture, reducing its overall stability while still contributing to higher creep deformation. Additionally, an excessive amount of fibers may disrupt the bitumen-fiber interaction, leading to reduced binder effectiveness and affecting the compactness and cohesion of the mix.

These findings highlight the existence of an optimal fiber content, beyond which the benefits of reinforcement are diminished. The 3% fiber mixture emerges as the most effective formulation, offering the best combination of stability and Marshall Quotient, which indicates an improved resistance to permanent deformation. However, fiber concentrations exceeding this threshold appear to negatively impact the mixture's overall mechanical balance, reinforcing the importance of carefully selecting an appropriate fiber dosage.

This study aligns with previous research findings, which suggest that while fibers enhance the performance of asphalt mixtures, their effectiveness is highly dependent on proper dispersion

and optimal content. Further investigations could focus on improving fiber distribution techniques, evaluating the long-term performance of fiber-reinforced mixtures under real traffic conditions, and assessing the impact of different fiber types on the Marshall Quotient and other mechanical properties.

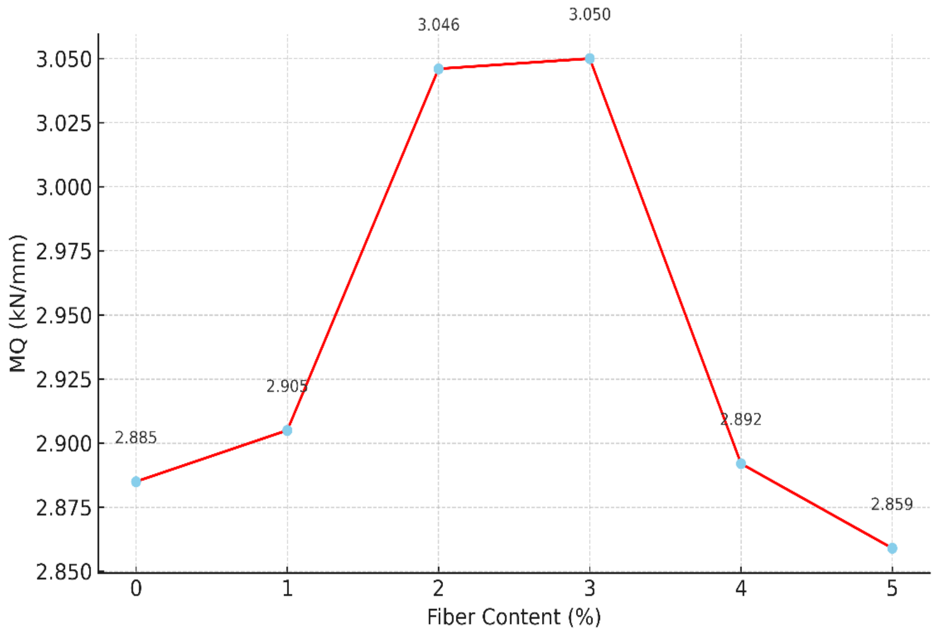

Figure 8. Evolution of Marshall Quotient with fiber content.

3.4. Evolution of Water Resistance

The experiment aims to evaluate the water resistance of the different bituminous mixtures.

The results are illustrated in **Figure 9**.

The analysis of water resistance evolution in fiber-reinforced bituminous mixtures reveals a significant improvement compared to pure bitumen. As shown in the results, the water resistance increases with fiber content, reaching its maximum value of 94.43% at 3% fiber content. Beyond this threshold, a slight decrease is observed for higher fiber contents (4% and 5%), where the resistance stabilizes while remaining above that of the control mix.

This trend suggests that fiber incorporation enhances the adhesion between bitumen and aggregates, improving the overall resistance of the mixture to moisture-induced damage. The initial increase in water resistance at 1% to 3% fiber content can be attributed to the reinforcing effect of the fibers, which may act as stabilizing agents by reducing the permeability of the asphalt

matrix. Additionally, fibers may contribute to a better bitumen-fiber interaction, leading to improved cohesion and reduced susceptibility to water infiltration.

The peak water resistance at 3% fiber content indicates that, at this concentration, the fibers are optimally distributed within the mixture, enhancing its durability against moisture-related degradation. However, beyond 3% fiber content, the slight decline and stabilization observed in water resistance may be due to fiber saturation within the bituminous matrix. Excessive fiber content could lead to fiber agglomeration, creating localized weak points that may slightly compromise the material's ability to resist water infiltration. Furthermore, at higher fiber concentrations, the risk of bitumen displacement increases, potentially leading to a reduction in aggregate-bitumen bonding efficiency.

Despite this slight decrease, the results indicate that fiber-modified mixtures consistently exhibit better water resistance than the control mix. This confirms that the addition of fibers effectively enhances the durability of bituminous mixtures, making them more resistant to the detrimental effects of moisture. These findings are particularly relevant for pavement applications, where water-induced damage such as stripping and raveling can significantly impact the longevity and structural integrity of asphalt surfaces.

Overall, the results highlight the importance of optimizing fiber dosage to achieve the best balance between moisture resistance and mechanical performance. While 3% fiber content appears to be the most effective, further studies could investigate long-term aging effects, different fiber types, and the impact of environmental conditions to refine the understanding of fiber-reinforced bituminous mixtures and their performance under real-world conditions.

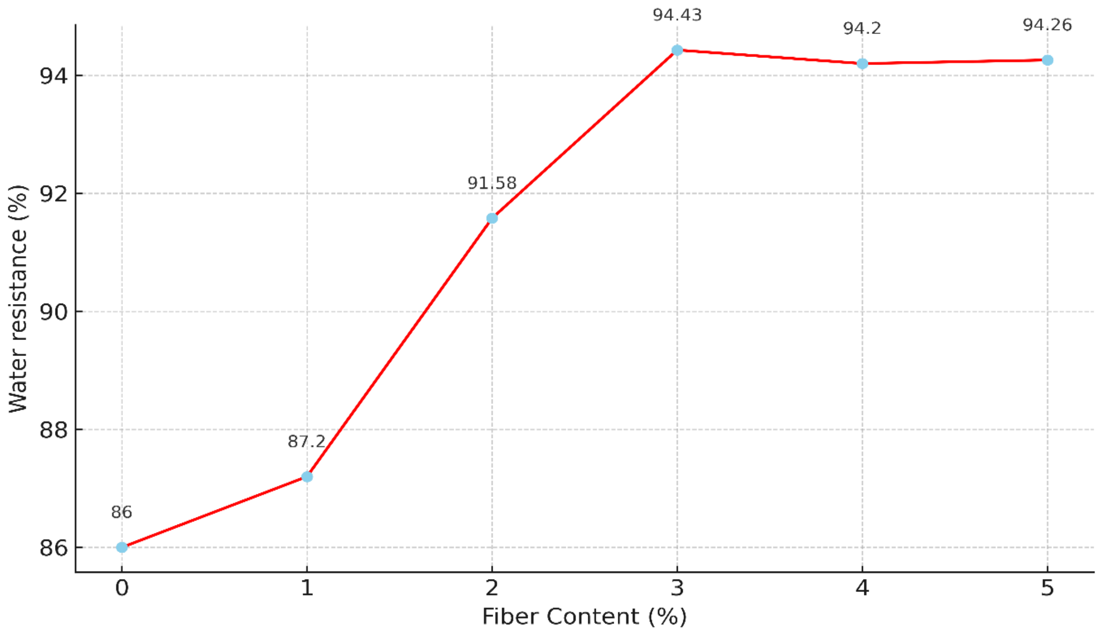

Figure 9. Evolution of water resistance with fiber content.

3.5. Creep Behavior

To facilitate a clear and structured comparison, the results are presented in two parts. First, we examine the influence of fiber content on deformation. Then, by keeping the fiber content constant, we analyze the impact of fiber length on the mixture's creep behavior.

3.5.1. Influence of Fiber Content

We aim to investigate the influence of fiber content on the creep behavior of asphalt mixtures, while keeping the fiber length parameter fixed. The study is conducted under a constant load of 10 kg and a temperature of 60 °C to ensure consistent testing conditions.

To analyze the effect of fiber content, we plot the deformation-recovery curves for each fiber-reinforced mixture and compare them with the control sample (**Figures 10–12**). These curves provide insights into the extent of permanent deformation and the ability of the material to recover after unloading. Additionally, to facilitate a quantitative comparison, bar graphs are plotted to visually assess the relative improvement in creep resistance for each mixture (**Figures 13–15**).

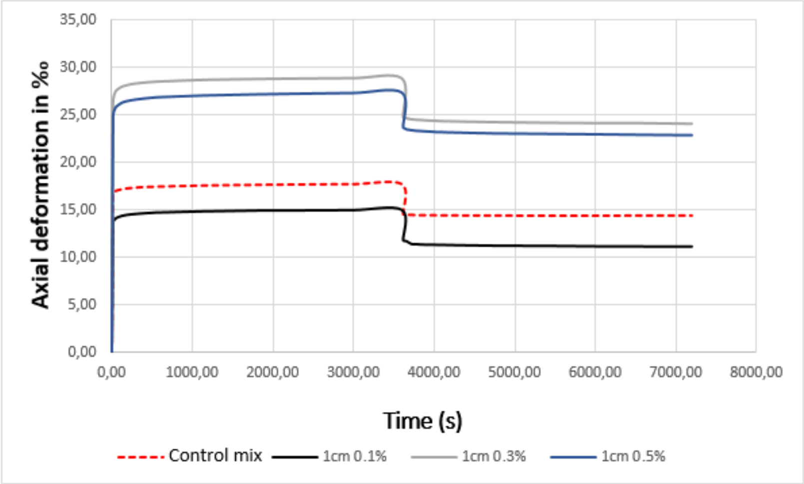

Figure 10. Creep-recovery curves for 1 cm fibers at different fiber contents.

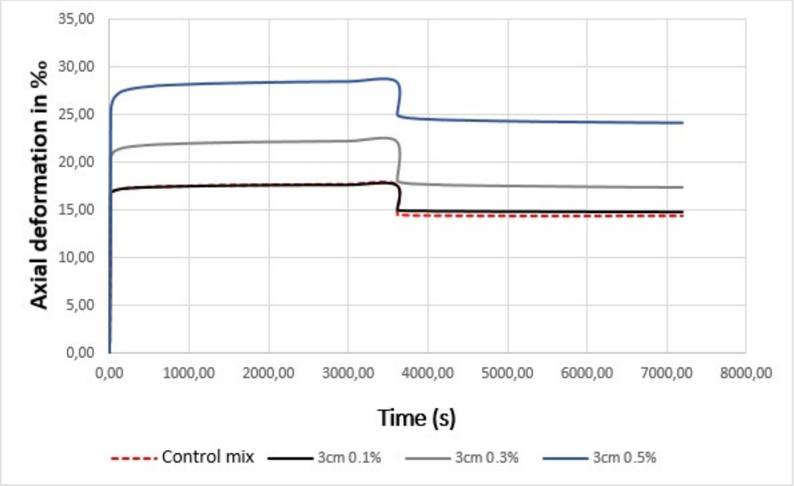

Figure 11. Creep-recovery curves for 3 cm fibers at different fiber contents.

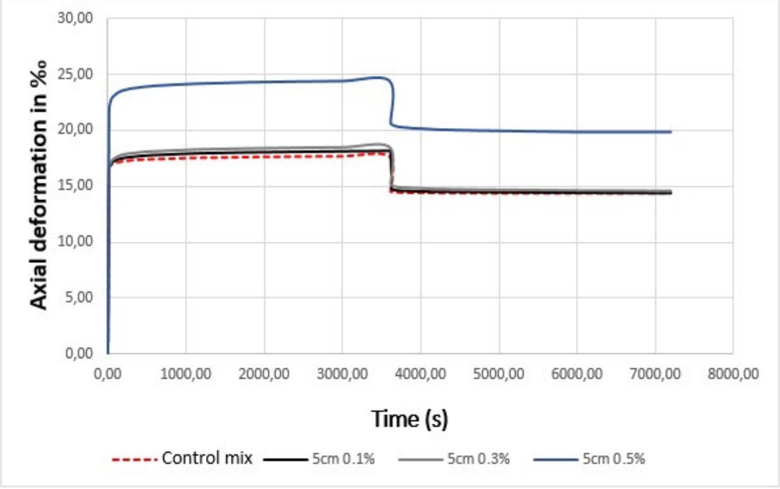

Figure 12. Creep-recovery curves for 5 cm fibers at different fiber contents.

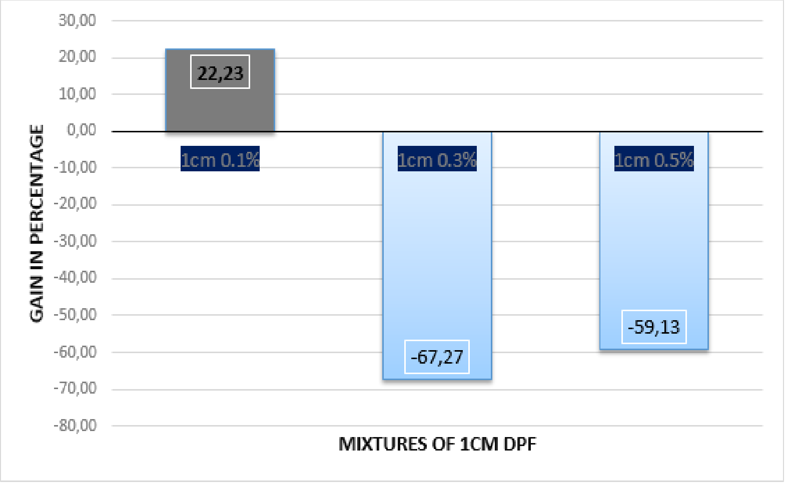

Figure 13. Improvements in 1 cm fiber mixtures.

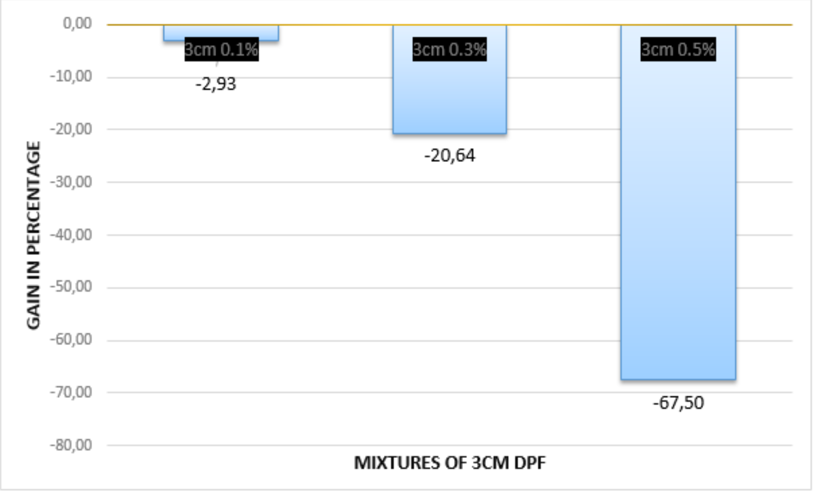

Figure 14. Improvements in 3 cm fiber mixtures.

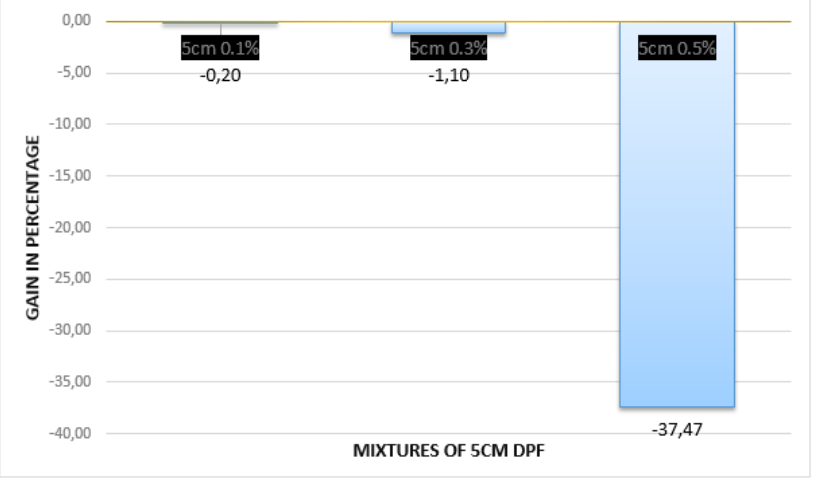

Figure 15. Improvements in 5 cm fiber mixtures.

3.5.2. Influence of Fiber Length

This study aims to investigate the influence of fiber length on the creep behavior of bituminous mixtures while keeping the fiber content parameter fixed. The experiments are conducted under a constant load of 10 kg and a temperature of 60 °C to ensure uniform testing conditions.

To assess the effect of fiber length, we plot the deformation-recovery curves for each fiber-reinforced mixture and compare them with the control sample (**Figures 16**–**18**). These curves allow us to evaluate the extent of permanent deformation and the material's ability to recover after unloading. Additionally, bar graphs are generated to visually compare the relative improvement in creep resistance for each mixture (**Figures 19**–**21**).

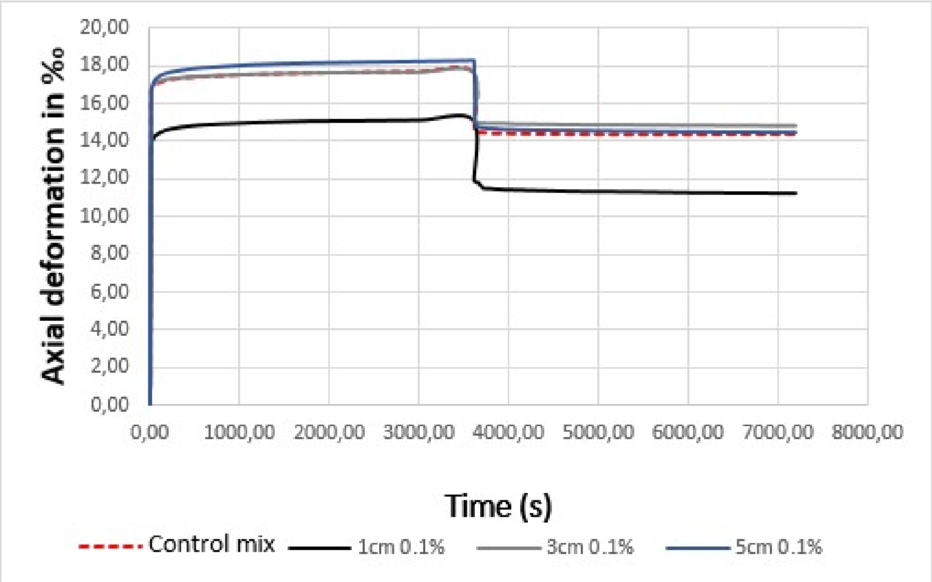

Figure 16. Creep-recovery curves of mixtures with 0.1% fiber content for different lengths.

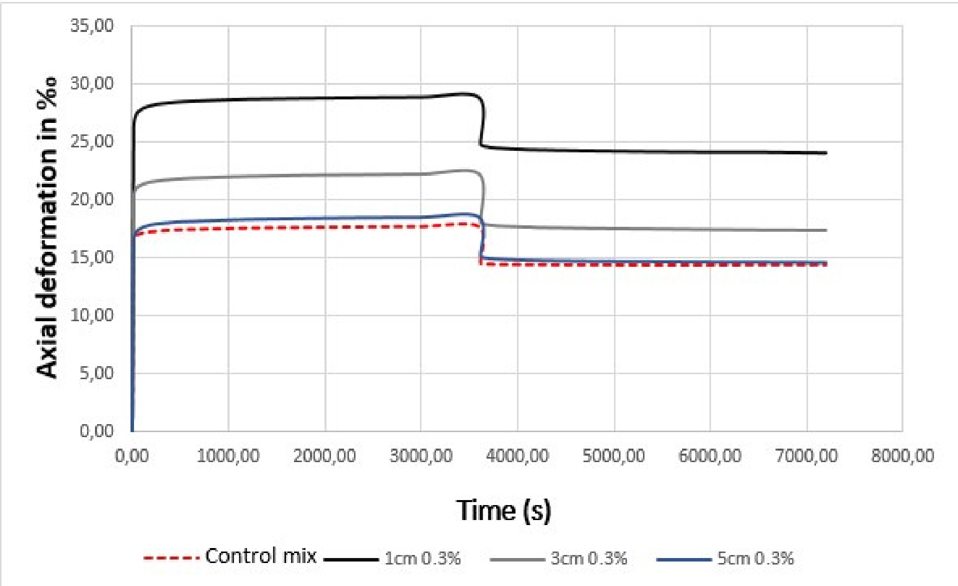

Figure 17. Creep-recovery curves of mixtures with 0.3% fiber content for different lengths.

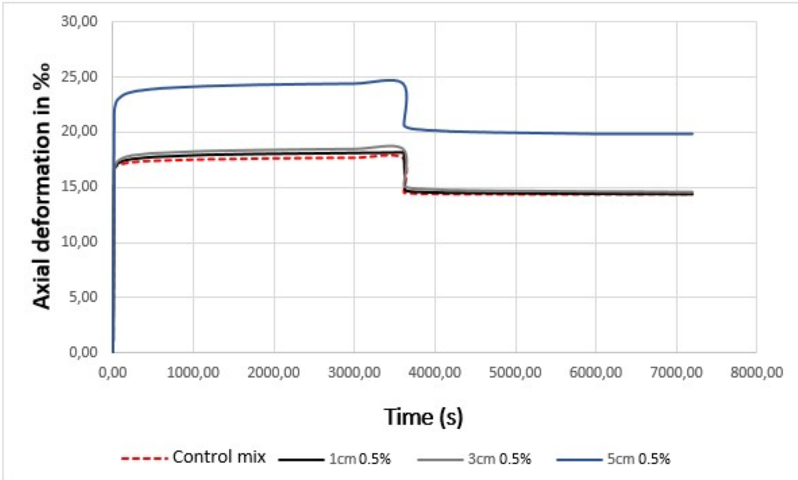

Figure 18. Creep-recovery curves of mixtures with 0.5% fiber content for different lengths.

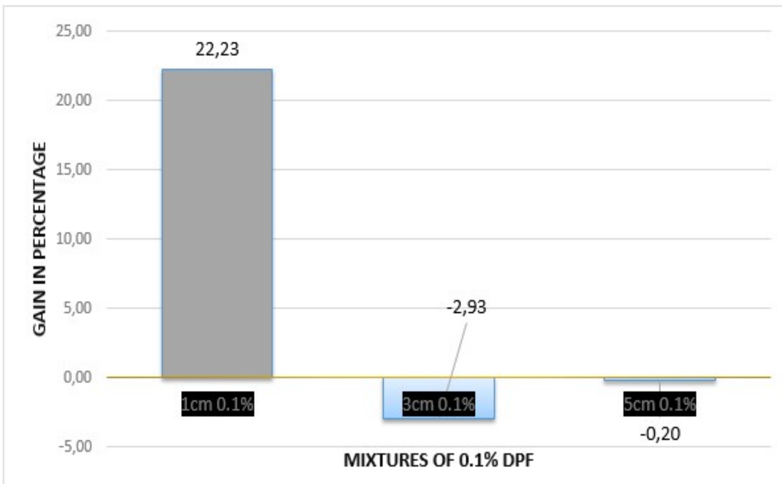

Figure 19. Improvements in mixtures with 0.1% fiber content.

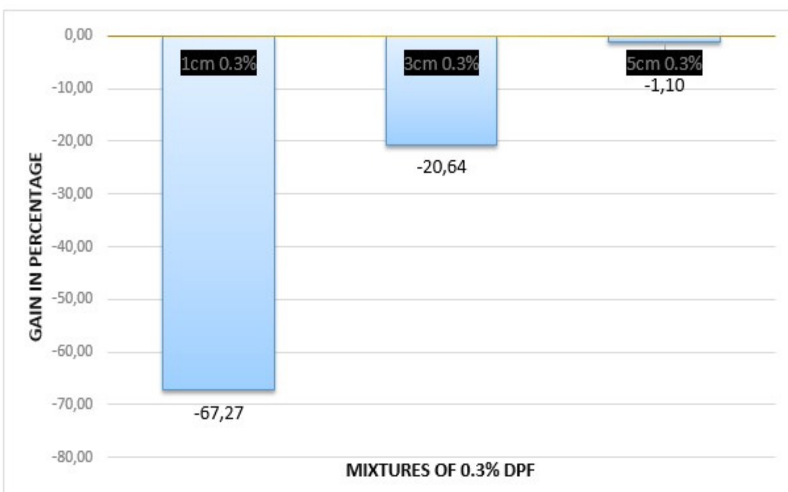

Figure 20. Improvements in mixtures with 0.3% fiber content.

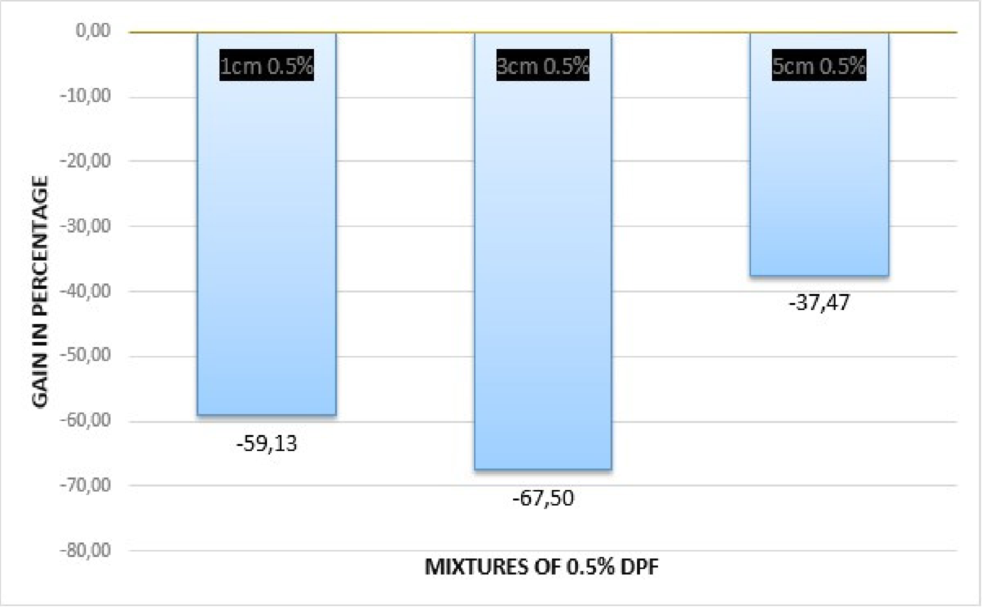

Figure 21. Improvements in mixtures with 0.5% fiber content.

The static creep tests revealed that all tested mixtures exhibited similar deformation curves, with each showing irreversible permanent deformation following the recovery phase. This suggests that, regardless of composition, the tested mixtures undergo residual strain, indicating a degree of susceptibility to permanent deformation. However, variations in creep resistance were observed across different fiber content levels, with notable exceptions in specific cases.

When assessing the mixtures based on their performance relative to the control mixture, fiber content plays a crucial role in creep resistance. The results indicate a general decline in creep resistance as fiber content increases, except for the mixtures incorporating a low fiber content of 0.1%. Notably, the mixtures containing 0.1% fiber content consistently exhibited the highest improvements in performance compared to other formulations, which experienced substantial reductions in creep resistance.

A more detailed analysis of fiber length within the 0.1% fiber content category reveals interesting trends. The mixture containing 1cm fibers demonstrated the most significant improvement, with a 22.23% increase in creep resistance. In contrast, the mixtures incorporating 3 cm and 5 cm fibers showed minimal performance gains, with reductions of less than 3%. This suggests that, at low fiber content levels, shorter fibers (1cm) contribute more effectively to structural reinforcement than longer fibers (3cm and 5cm). However, beyond this low content threshold, fiber length alone does not provide a clear indication of performance improvements, as the influence of other factors—such as fiber distribution, orientation, and interaction with the matrix—becomes more significant.

Moreover, the inverse relationship between fiber content and static creep resistance is particularly evident. As fiber content increases, the percentage of voids in the mixture also tends to rise, leading to higher susceptibility to deformation under load. This trend is further supported by the bar graph plotted from the PCG test, which highlights the proportional relationship between fiber content and void percentage for selected mixtures. The presence of excessive fibers may disrupt the compactness of the mixture, reducing its ability to resist permanent deformation.

In summary, while the incorporation of low fiber content (0.1%) enhances creep resistance. particularly with shorter fiber lengths and higher fiber contents appear to compromise the mechanical integrity of the mixtures. These findings emphasize the importance of optimizing fiber content and length to achieve an optimal balance between reinforcement and workability in asphalt mixtures (**Figure 22**).

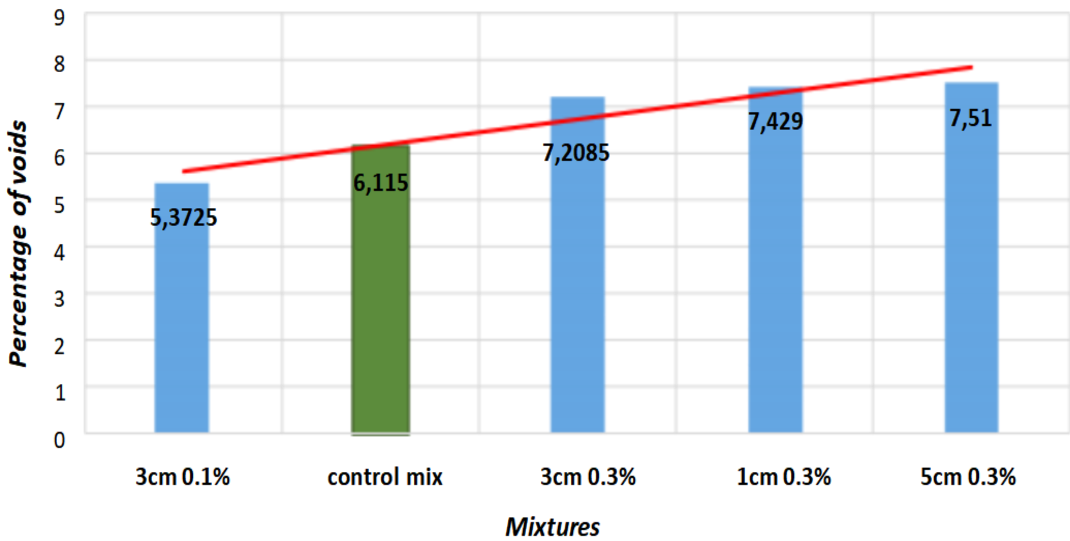

Figure 22. Percentage of voids for some mixtures.

3.6. Rutting Behavior

The test aims to evaluate, under given testing conditions, the rutting resistance of a bituminous mixture prepared and compacted in the laboratory. The rutting tests were conducted at the laboratory of EPTRC (Public Roadworks Company) in Berrouaghia, Medea Province, in the north region of Algeria. They allowed us to perform the test for five (05) mixtures: control, 1 cm 0.3%, 3 cm 0.1%, 3 cm 0.3%, and 5 cm 0.3%.

The graph shown in **Figure 23** illustrates the Rutting curves ln(RD) = fct(ln(N)). It is plotted as ln(RD) versus ln(N) for each specimen of the same composition subjected to the test. The values of the rut depth percentage (RD) at N load cycles are excluded if the rut depth exceeds 15% of the specimen's thickness after N load cycles [32].

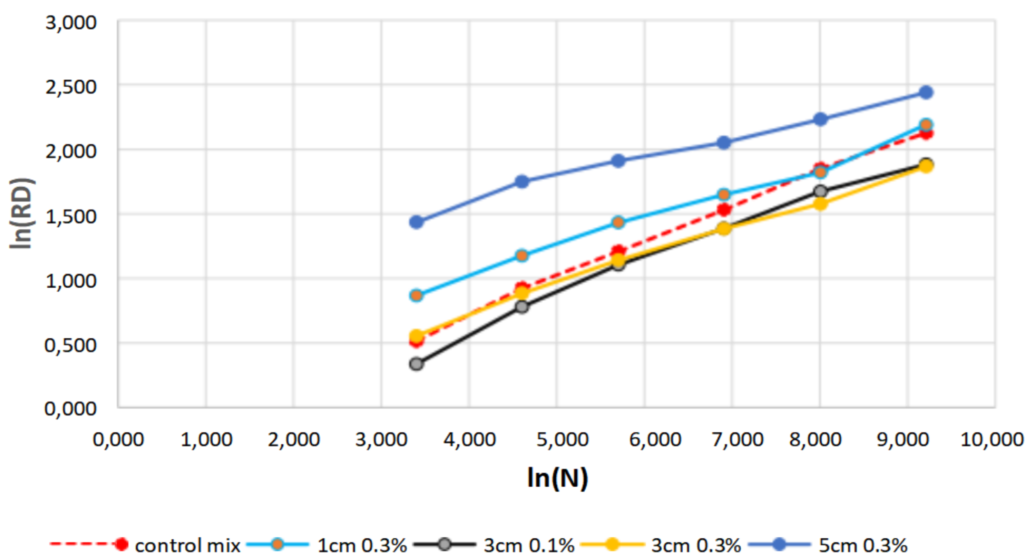

Figure 23. Rutting curves ln(RD) = fct(ln(N)).

The rutting tests (**Figure 24**) demonstrated that all tested mixtures followed a consistent linear trend, with the general Equation (3).

$$Ln\ (RD) = a \times \ln\ (N) + b \tag{3}$$

Where RD represents the rut depth and N is the number of loading cycles. This logarithmic relationship indicates a predictable evolution of rutting over time across all mixtures.

To facilitate a comparative analysis, the results were evaluated at the final testing stage, N = 10,000 cycles (ln(N) = 9.21). The findings reveal that the [3cm 0.1%] and [3cm 0.3%] mixtures exhibited superior rutting resistance compared to the control mixture. In contrast, the [1cm 0.3%] and [5cm 0.3%] mixtures displayed poorer performance, suggesting that fiber characteristics significantly influence the resistance to permanent deformation.

When analyzing mixtures with the same fiber content (0.3%), the 3cm fiber mixtures outperformed both the 1cm and 5cm fiber mixtures in rutting resistance. This highlights that fiber length plays a critical role in reinforcing the mix, with 3cm fibers providing optimal structural benefits under repeated loading conditions. Conversely, the 5cm fiber mixture showed a significant deterioration, with a decline of over 14% in performance, indicating that excessively long fibers may negatively impact mixture stability.

Further analysis of the two 3cm fiber mixtures (0.1% and 0.3%) reveals only a marginal difference of 0.8% in rutting resistance improvement. This suggests that, beyond a certain threshold, increasing fiber content does not necessarily yield substantial additional benefits in rutting resistance.

Overall, the results emphasize the importance of optimizing fiber length and content to achieve enhanced rutting resistance. The findings suggest that a fiber length of 3 cm provides the best performance, while excessively short or long fibers may compromise the mix's stability and effectiveness in mitigating permanent deformation.

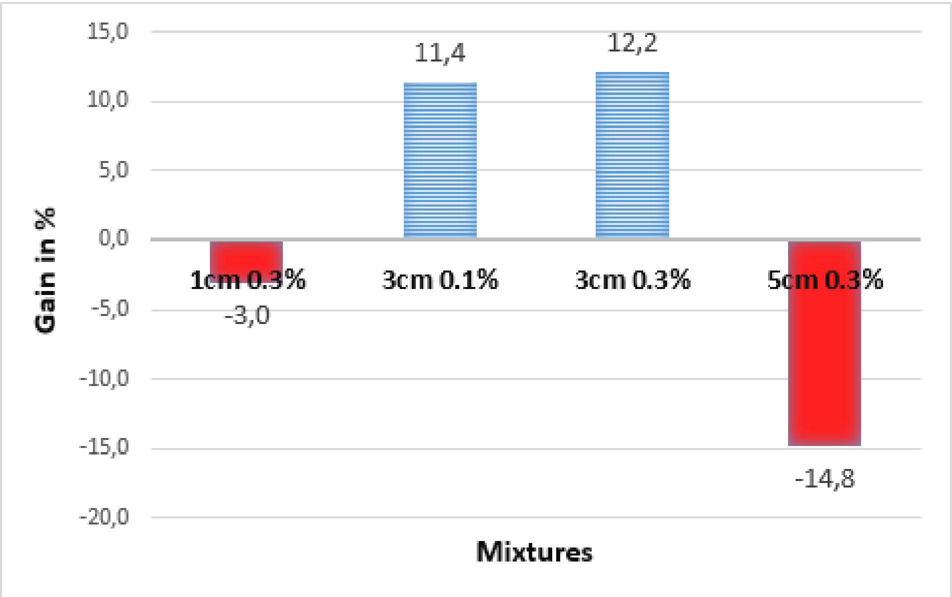

Figure 24. Improvement in rutting resistance for different mixtures.

3.7. Wet vs. Dry Process Comparison

The comparative analysis between wet and dry fiber incorporation methods, as summarized in **Table 6**, reveals distinct performance advantages for each approach, highlighting the nuanced role of fiber dispersion and matrix interaction in governing mechanical properties. The wet process, wherein date palm fibers (DPF) are pre-blended with bitumen, demonstrated superior Marshall stability (27% higher at 3% fiber content) compared to the dry process. This enhancement can be attributed to the homogeneous distribution of fibers within the bituminous matrix, which optimizes stress transfer and interfacial adhesion. The pre-mixing step in the wet process ensures thorough fiber coating by bitumen, reducing fiber agglomeration and promoting a more cohesive composite structure. This aligns with prior studies emphasizing that fiber-bitumen compatibility is critical for stability improvements, as it mitigates weak zones and enhances load-bearing capacity [5,19].

Table 6. Comparative analysis of wet and dry fiber incorporation methods.

Parameter	Wet Process (3% DPF)	Dry Process (3 cm, 0.3% DPF)	Performance Difference
Marshall Stability	35.7% increase vs. control	Moderate improvement	+27% for wet process
Rutting Resistance	Moderate improvement	14% increase vs. control	+14% for dry process
Creep Resistance	Best at 2% DPF (not 3%)	Best at 0.1% DPF (any length)	No direct correlation
Water Resistance	Peak at 3% DPF (94.43%)	Not explicitly tested	Wet process superior
Workability	Reduced at > 3% DPF	Less affected by fiber length	Dry process more adaptable

Conversely, the dry process—where fibers are mixed directly with aggregates—exhibited superior rutting resistance (+14% with 3 cm/0.3% fibers). This suggests that dry incorporation may better preserve fiber integrity and interlocking with aggregates, thereby resisting shear deformation under dynamic loads. The 3cm fibers, in particular, likely strike an optimal balance between length and dispersibility, creating a reinforcing network that hinders aggregate displacement without compromising workability. This finding corroborates research indicating that longer fibers enhance rutting resistance by bridging cracks and redistributing traffic-induced stresses [2,15].

The dichotomy between stability (wet) and rutting resistance (dry) underscores the deformation-dependent behavior of fiber-reinforced mixtures. While the wet process maximizes static properties like stability through matrix-level reinforcement, the dry process excels in dynamic performance by leveraging fiber-aggregate interaction. This divergence may reflect the distinct mechanisms governing each test: Marshall stability measures resistance to instantaneous deformation, whereas rutting evaluates cumulative strain under repeated loading. Notably, the absence of a direct correlation between creep and rutting resistance further supports the hypothesis that fiber efficacy is domain-specific, contingent on whether deformation arises from static (creep) or dynamic (rutting) conditions [4,18].

4. Conclusion

In this study, the mechanical performance of bituminous mixtures modified with DPFs was investigated using both wet and dry incorporation methods, with particular attention given to the effects of fiber content and length on creep and rutting behavior. In the wet process, DPFs were pre-mixed with bitumen, and five fiber-reinforced mixtures (1%–5%) along with a control mix were prepared, while in the dry process, nine fiber-reinforced mixtures were fabricated by varying fiber length (1, 3, and 5 cm) and content (0.1%–0.5%). A standard mix design was first established to ensure consistency across all tests. The results indicated that the 3% fiber content in the wet process provided the best overall enhancement in Marshall stability, water resistance, and Marshall Quotient, suggesting that this concentration optimally reinforces the bituminous matrix by improving adhesion and limiting moisture-related damage. Additionally, the 2% fiber content demonstrated superior creep resistance, which is particularly relevant for resisting permanent deformation under repeated loading. In contrast, dry-process mixtures with 3 cm fibers showed the highest rutting resistance, while those with 0.1% fiber content exhibited the best creep performance. However, no direct correlation was found between rutting and creep behaviors—likely due to the differing deformation domains associated with each test. A uniaxial static creep test was also developed using oedometric equipment, enabling controlled stress and temperature conditions. It was observed that higher fiber contents generally reduced creep resistance, possibly due to increased void content, highlighting the need to further investigate volumetric properties. Based on the outcomes, several recommendations are proposed: replace the 1% and 5% fiber mixtures with 2.5% and 3.5% in the wet process; conduct void content measurements across all samples to clarify the observed trends in creep resistance; perform rutting tests on the [1 cm, 0.1%] mixture, which yielded the best creep resistance; and replace 5 cm fibers with 2 cm fibers while adjusting contents to 0.2% and 0.4%. Overall, the incorporation of DPF has been confirmed as a promising, sustainable reinforcement strategy for asphalt mixtures, contributing to improved mechanical performance and durability while promoting the valorization of agricultural waste in road construction.

5. Recommendations

- Validate laboratory findings through pilot-scale field trials under real traffic and climatic conditions, monitoring long-term durability (e.g., aging, moisture damage).
- Compare DPF performance with other natural/synthetic fibers (e.g., sisal, polypropylene) to establish broader applicability.
- Develop predictive models linking fiber properties to mixture performance using machine learning or finite element analysis.

Author Contributions

Conceptualization, S.A.F.; methodology, S.A.F.; software, S.A.F. and K.R.; validation, S.A.F. and K.R.; formal analysis, S.A.F.; investigation, S.A.F.; data curation, S.A.F.; writing—original draft preparation, S.A.F.; writing—review and editing, S.A.F. and K.R.; visualization, S.A.F.; supervision, K.R.; project administration, S.A.F. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

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Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

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