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Optimizing the Composition of Fiber-Reinforced Concrete Airfield Pavements to Improve Performance and Prevent Cracking

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Abstract. Concrete airfield pavements often experience premature failure due to extensive cracking under repeated loading and environmental exposure. Traditional single-scale fiber reinforcement methods have proven inadequate in controlling both micro- and macro-cracks, prompting the need for hybrid solutions. This study investigates the mechanical and durability performance of concrete reinforced with hybrid combinations of micro basalt and macro basalt fibers. The main objectives were to evaluate the synergistic effects of dual-scale fiber reinforcement on crack resistance, elasticity, density, and water-related durability properties, and to determine the optimal fiber combination for high-performance pavement concrete. A comprehensive experimental program was conducted involving 25 concrete mixes with varying proportions of micro basalt and macro basalt fibers. Parameters such as elastic modulus, dry and saturated density, water absorption, and moisture content were measured and analyzed. The methodology employed standard mechanical testing protocols and statistical comparisons to identify trends and correlations. Results revealed that combinations such as 1.5A1.5B and 1.5A0.5B achieved superior elasticity (up to 53.65 GPa) and optimal balance across densities and water absorption. While fiber inclusion had minimal influence on compressive strength, basalt fibers significantly improved tensile and flexural behavior, toughness, and resistance to environmental degradation. The hybrid mixes demonstrated reduced porosity and water absorption, enhancing long-term durability. In conclusion, dual-scale hybrid fiber reinforcement offers a viable strategy for enhancing crack control, elasticity, and durability in concrete airfield pavements. It is recommended that future pavement designs incorporate optimized micro basalt and macro basalt fibers combinations to extend service life, reduce maintenance, and promote sustainable infrastructure development.

Keywords: basalt fiber, fiber reinforced concrete pavement, concrete airfield pavements concrete, moisture resistance, concrete crack mitigation, concrete properties, single-scale fiber reinforcement, dual-scale hybrid fiber reinforcement

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Оптимизация состава фибробетонных аэродромных покрытий для повышения эксплуатационных характеристик и предотвращения образования трещин

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Аннотация. Изучены механические свойства и долговечность бетона, армированного гибридными комбинациями микробазальтовых и макробазальтовых волокон. Цель исследования – оценка эффективности двухмасштабного гибридного армирования бетона микробазальтовыми и макробазальтовыми волокнами для повышения трещиностойкости, эластичности, плотности и водостойкости, а также определение оптимальной комбинации волокон для применения в аэродромных покрытиях. Проведена всесторонняя экспериментальная программа, включающая 25 бетонных смесей с различным соотношением микробазальтовых и макробазальтовых волокон. Измерялись и анализировались такие параметры, как модуль упругости, плотность в сухом и насыщенном состоянии, водопоглощение и влажность. В качестве методов исследования использовались стандартные протоколы механических испытаний и статистические сравнения для выявления тенденций и корреляций. Результаты показали, что такие комбинации, как 1,5A1,5B и 1,5A0,5B, обеспечивают превосходную эластичность (до 53,65 ГПа) и оптимальный баланс плотности и водопоглощения. Добавление волокон оказывало минимальное влияние на прочность при сжатии, базальтовые волокна значительно улучшали прочностные характеристики при растяжении и изгибе, ударную вязкость и устойчивость к воздействию окружающей среды. Гибридные смеси характеризовались снижением пористости и водопоглощения, что способствовало увеличению долговечности. Двухмасштабное гибридное армирование волокнами является эффективной технологией для повышения эксплуатационных характеристик и долговечности бетонных покрытий. Рекомендуется использование оптимизированных комбинаций микробазальтовых и макробазальтовых волокон для продления срока службы конструкций и снижения затрат на обслуживание.

Ключевые слова: базальтовое волокно, фибробетонное покрытие, влагостойкость бетона, предотвращение образования трещин в бетоне, свойства бетона, одномасштабное дисперсное армирование, двухмасштабное гибридное армирование

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1. Introduction

Fibers are added to concrete to improve its natural weakness and brittleness in tension [1]. Corrugated steel fibers with large diameters are commonly used because they are affordable, spread well in the mix, and do not greatly affect workability. However, their large size often makes them less efficient, and they do not improve the toughness of fiber-reinforced concrete (FRC) very much [2]. Natural fibers offer some clear benefits over synthetic ones, like being biodegradable, lighter in weight, and cheaper. But using them in composites is still difficult due to inconsistent quality, lower strength, high water absorption, and poor resistance to heat [3]. Steel fibers, while helpful in improving strength, can reduce concrete workability and increase shrinkage during hardening. Hybrid fiber combinations, such as mixing long hooked-end steel fibers with others, have shown the ability to improve compressive strength more effectively than mono fibers [4]. In another study, combining steel, palm, and synthetic fibers led to better flexural toughness and tensile strength in high-strength flowing concrete [5]. Changing the fiber layering pattern also gives engineers more freedom to design composites with better performance. Additionally, modifying the concrete matrix with nanoparticles is gaining attention because it can add extra features and improve durability [6].

1.1. Concrete in Pavement Construction

Concrete has become increasingly prominent in road construction over the past decade, largely due to its inherent durability. Nonetheless, conventional concrete is limited by its low tensile strength, poor ductility, and insufficient energy dissipation capacity [7]. It is widely recognized that unreinforced concrete tends to fail abruptly when subjected to tensile or flexural stresses, necessitating the use of larger structural dimensions in such scenarios. The introduction of discrete fibers into plain concrete significantly enhances its ductility and tensile capacity. As a result, fiber-reinforced concrete (FRC) allows for reduced cross-sectional dimensions under the same tensile loads compared to plain concrete [8].

In pavement applications, high early-strength concrete is frequently selected, particularly for replacement work. However, such mixes are often susceptible to premature cracking due to the high heat of hydration, which contributes to plastic shrinkage. FRC has demonstrated excellent resistance to plastic shrinkage and has been effectively employed in construction, especially in slab-on-grade systems [9]. To enhance the overall performance of rigid pavements, materials must possess adequate resistance to cracking, a predominant mode of structural failure. Incorporating fibers into concrete to produce a pseudo-ductile matrix has shown great promise in meeting these performance demands. Despite the established effectiveness of FRC in pavement systems, its broader adoption is hindered by inconsistent standards regarding design practices and field implementation [10].

1.2. Crack Detection and Rehabilitation

Crack detection plays a foundational role in highway maintenance strategies, with cracking being the most visible form of surface distress. In recent years, digital image processing techniques have become increasingly prevalent for the identification and classification of pavement cracks [11].

Typical crack types observed in pavements include fatigue, longitudinal, transverse, block, slippage, reflective, and edge cracks [12]. One widely adopted rehabilitation technique involves overlaying deteriorated Portland cement concrete (PCC) pavements with asphalt concrete (AC). While cost-effective, this approach often leads to the rapid emergence of reflective cracks due to pre-existing joints or fissures within the PCC substrate [13].

Advanced computational modeling techniques have gained traction in recent years, particularly the phase field method for analyzing fatigue crack growth. Within this domain, the phase field cohesive zone method (PF-CZM) has emerged as a robust framework for simulating fracture mechanisms in quasi-brittle materials like concrete. Recent work has further extended the utility of PF-CZM to encompass fatigue-induced crack propagation scenarios [14].

1.3. Use of Basalt Fibers in Concrete

Basalt fiber–reinforced concrete (BFRC) has emerged as a promising alternative to conventional concrete reinforcement methods, particularly due to its enhanced toughness index, energy absorption capacity, and superior tensile and bond strength. These improvements are especially notable when basalt fibers are utilized in chopped or minibar forms, allowing for more effective load distribution and crack control within the concrete matrix [15]. Experimental studies have shown that the incorporation of basalt fibers produces varied effects across different mechanical properties. In [16], it was observed that while the inclusion of basalt fibers did not significantly influence the compressive strength or elastic modulus of concrete, it considerably improved the splitting tensile and flexural strengths. Notably, the enhancement in tensile strength increased proportionally with fiber dosage, a trend not equally mirrored by glass fiber–reinforced concrete (GFRC), which showed limited improvements beyond a 0.5% dosage. Furthermore, fracture energy for both basalt and glass fiber–reinforced specimens saw substantial increases with fiber contents exceeding 0.25%, indicating that even small additions of basalt fiber can significantly enhance crack energy dissipation.

In study [17], the effect of various types of polydisperse basalt reinforcement on increasing the strength and frost resistance of high-strength basalt concrete with coarse aggregate modified with the “Embelit 8-100” additive was experimentally studied. It was found that the addition of soft basalt fiber to the composition of high-strength concrete increases its frost resistance.

Basalt fibers are also praised for their eco-friendly production processes and mechanical robustness, contributing to their growing popularity. In [18], two basalt fiber forms were compared, bundle dispersion fibers and minibars, and their mechanical performance through flexural testing and drop-weight impact methods was evaluated. While both fiber types were effective in improving pre-cracking strength, minibars proved particularly beneficial in enhancing post-cracking behavior, likely due to the polymer coating that improves their durability and anchorage within the matrix. This distinction underlines the importance of fiber form and surface treatment in determining mechanical performance outcomes. The authors of [19] proposed a correlation coefficient-based model to predict the mechanical behavior of BFRC. Their findings supported the assertion that basalt fiber primarily enhances the toughness and crack resistance of concrete, with a more pronounced effect on tensile and flexural strength than on compressive strength. Optimum improvements were noted at fiber contents between 0.3 and 0.4%, suggesting a threshold beyond which further gains may plateau or diminish. In another investigation, the authors of [20] analyzed BFRC within a volume fraction range of 0–2%, assessing key mechanical parameters such as compressive strength, tensile strength, and modulus of rupture. Their findings corroborated earlier studies, revealing that while compressive strength saw minimal gains, tensile properties and rupture modulus improved significantly. At a fiber volume fraction of 1.5%, increases of 4.45, 22, and 57% were recorded for compressive strength, tensile strength, and modulus of rupture, respectively, when compared to unreinforced concrete. These studies collectively affirm that basalt fibers, particularly in optimized dosages and appropriate physical forms, substantially improve the mechanical performance of concrete, especially in terms of crack resistance, toughness, and tensile strength. As such, basalt fibers stand out as an ideal material for enhancing the performance of concrete airfield pavements subjected to high stress and frequent crack initiation. The incorporation of short discrete fibers into concrete — especially in low volume fractions (typically below 2–3%) — has proven effective in enhancing the fracture toughness of the composite material. This increase in toughness contributes significantly to controlling crack width and preventing crack propagation under stress [21].

Microfibers, generally characterized by lengths under 10 mm and diameters ranging from 25 to 40 μm, possess exceptionally high specific surface areas (exceeding 200 cm^2/g). This trait results in a high fiber density within the concrete matrix, enabling more robust crack-bridging mechanisms at the micro-level. Consequently, these fibers effectively counteract microcracking induced by thermal and mechanical shrinkage, thus contributing to enhanced durability and crack resistance [22]. Despite their mechanical benefits, certain fibers negatively impact the workability of concrete. For instance, study [23] reported substantial reductions in slump when using glass and nylon fibers — by 37.5% and 68.7%, respectively —

indicating decreased workability due to increased internal friction and reduced flowability. Recent developments in hybrid fiber-reinforced concrete (HyFRC) further demonstrate the synergistic effect of combining fibers of different sizes and properties. In [24], it was shown that HyFRC slabs offer improved load-carrying capacity, reduced reinforcement stress, enhanced crack resistance, and minimized deflection compared to conventional concrete slabs. These improvements are attributed to the integration of both micro and macro fibers, which create a multi-scale reinforcement network within the matrix.

Macro synthetic fibers such as polypropylene (PP), polyethylene (PE), and polyvinyl alcohol (PVA) are widely adopted in structural applications including pavements, tunnels, and industrial floors. While their general application is well established, their specific role in controlling crack widths in pavement systems remains underexplored [25]. These fibers serve as reinforcing meshes within the concrete, bridging cracks and enhancing post-cracking strength, toughness, and ductility. The strategic inclusion of such fibers has been shown to reduce crack widths and frequency, thereby increasing the lifespan of concrete structures under dynamic loads and aggressive environmental conditions. Study [26] further compared macro fibers to bundled multifilament microfibers within strain-hardening cementitious composites. Results showed that microfibers at higher dosages (1–4%) outperformed macro fibers significantly, achieving up to 200% higher tensile strength and over 400% increased post-cracking stiffness. Notably, microfibers at a 4% volume fraction improved crack strength and ultimate strength by 51 and 30%, respectively, leading to finer crack distributions and enhanced ductility — key attributes for lightweight and durable construction. Similarly, study [27] demonstrated the use of hardwood pulp fibers in mitigating early-age cracking. At a dosage of 0.75%, these bio-based fibers delayed cracking through internal curing and stress reduction mechanisms, reducing crack widths by 88% while also improving toughness and tensile capacity. This suggests a potential for self-healing capabilities in cementitious materials reinforced with natural fibers.

Collectively, these findings highlight the pivotal role of both micro and macro fibers in enhancing concrete's mechanical performance. Their combined use in hybrid configurations allows engineers to optimize strength, crack resistance, and service life in concrete airfield pavements and other structural applications, making fiber-reinforced concrete a more resilient and sustainable choice for modern infrastructure. The increasing emphasis on sustainability in material science has propelled the adoption of natural fibers in composite development, driven by the need to create eco-friendly, cost-effective, and high-performance building materials. Both academic researchers and industry practitioners are increasingly turning to natural fiber-reinforced composites as viable alternatives to traditional synthetic fiber [28]. Among the various natural fibers — categorized broadly into plant-based, animal-based, and mineral-based — basalt fibers (BFs) stand out due to their superior mechanical properties, thermal stability, and resistance to environmental degradation [29].

Recent experimental studies have demonstrated the performance-enhancing potential of basalt fibers in concrete, particularly when used in combination with other materials. Study [30] explored the mechanical and durability characteristics of hybrid fiber-reinforced concrete (HFRC) incorporating basalt fibers, polypropylene fibers (PPF), and rubber particles. Using an orthogonal design method, they assessed the contribution of each component to mechanical strength and carbonation resistance. Results indicated that when basalt fiber content was optimized at 0.2% and PPF at 0.15%, the HFRC exhibited significantly improved mechanical properties and resistance to environmental degradation.

Similarly, the authors of [31] evaluated the performance of basalt fiber-reinforced cement mortar subjected to unilateral salt-freezing conditions. Their results confirmed that even a modest inclusion of basalt fibers could dramatically enhance the durability of the mortar. At an optimal dosage of 1.2 kg/m^3, the specimens displayed improved compressive and flexural strength, with significantly reduced internal porosity compared to the control specimens. This affirms the role of basalt fiber in reducing permeability and improving freeze-thaw resistance, which is critical for infrastructure exposed to harsh environmental cycles. The versatility of basalt fibers has also been demonstrated in combination with supplementary cementitious materials. In study [32], lightweight aggregate concrete (LWAC) was developed using ultrafine ground granulated blast furnace slag (UGGBS) and its mechanical properties had a substantial enhancement when

BF and coconut shells were incorporated. As a significant finding of this research, a grade 30 LWAC with a demolded density of 1864 kg/m^3 containing only 284 kg/m^3 cement was developed. Despite extensive studies on fiber-reinforced concrete, most research has focused primarily on mechanical properties with other kinds of fibers like glass, carbon, steel, and natural fibers, there is also limited attention to how other key properties, such as stiffness (elastic modulus), density, and moisture resistance, contribute to crack mitigation in pavement applications. Moreover, while basalt fibers have shown promise as a sustainable and high-performance reinforcement material, the effects of combining micro and macro basalt fibers in optimized ratios remain vague, particularly in relation to their influence on both early-age microcrack control and long-term macrocrack resistance. There is a clear need for studies that link improvements in elastic modulus, densification, and water-related durability to the mechanisms of multi-scale crack mitigation in pavement-grade concrete.

Crack formation is a critical mode of failure in pavement concrete, especially under high mechanical stress and environmental exposure. Traditional reinforcement strategies often fail to address both early-age shrinkage and service-load cracking. Basalt fibers, with their superior tensile strength and chemical stability, present a sustainable alternative to synthetic and steel fibers. However, existing studies have predominantly focused on single-scale fiber inclusion. This study is therefore justified by the need to explore hybrid micro–macro basalt fiber systems, aiming to harness the benefits of multi-scale crack control. By linking fiber configuration to mechanical performance, density, and water permeability, this research fills a vital gap in the design of high-performance, durable pavement concrete.

1.4. Aim and Objectives

This study aims to investigate the synergistic effects of hybridized basalt microfibers and macro fibers on the mechanical strength, densification, and moisture resistance of concrete developed for high-stress pavement applications. By varying the ratios of micro to macro basalt fibers, the research seeks to identify optimal combinations that can simultaneously mitigate both micro- and macro-scale cracking, while maintaining structural integrity and durability under repetitive loading conditions. The objectives of this study are:

1) to assess the individual and combined effects of basalt microfibers and macro fibers on the mechanical properties of concrete, including compressive strength, flexural strength, and elastic modulus;

2) to evaluate the influence of fiber hybridization on concrete densification by measuring dry, saturated, and air-dried densities;

3) to examine the water absorption characteristics of different fiber-reinforced mixes using both air-drying and oven-drying methods as indicators of durability;

4) to determine the most effective micro–macro fiber ratio for dual crack mitigation, balancing early-age microcrack control with post-crack load transfer performance.

2. Materials and Methods

2.1. Materials for Experiment

The quality and performance of concrete are significantly influenced by the physical and chemical characteristics of its constituent materials. In this study, a tailored selection of materials was made to meet the mechanical, durability, and crack control demands of pavement-grade concrete.

2.1.1. Cement

The binder used was Portland Cement M600, sourced from Akkermann Cement, which conforms to the CEM I 52.5 classification under GOST 31108-2020.[1] This type of cement is recognized for its rapid early strength development, making it ideal for rigid pavements subjected to heavy loads and early traffic reopening. Its fast-setting nature also minimizes construction time, enhancing productivity on-site while ensuring durability and long-term performance under cyclic stress.

[1] GOST 31108 2020. *Cements for general construction. Specifications.* Interstate Technical Committee for Standardization in Construction. 2020.

2.1.2. Water

Potable (drinking) water was used for mixing to ensure that it was compatible with cement hydration and durability standards. The water used for mixing fiber concrete mixture met the requirements of GOST 23732-79.[2] Since drinking water per GOST 2874-82[3] is deemed suitable for mixing without additional quality checks, it guarantees a consistent hydration process essential for strength development and long-term durability.

2.1.3. Superplasticizer

To enhance workability at a low water-cement ratio, Polyplast Target was incorporated at 0.7% of the cement weight. This polycarboxylate-based admixture comes in two types. Type 1 integrates air-entraining agents, improving freeze–thaw resistance and rheology. Type 2 includes accelerators and structural modifiers that enhance early strength gain and cohesiveness. Both types comply with GOST 30459-2008[4] and TU 5745-081-58042865-2015, providing reliable performance in high-strength fiber-reinforced concrete applications. The plasticizer aids in uniform fiber distribution and matrix cohesion, supporting resistance to crack initiation and propagation.

2.1.4. Aggregates

The concrete incorporated locally sourced fine and coarse aggregates. Fine aggregates consisted of natural medium sands which met GOST 8736-93,[5] with a fineness modulus of 2.0–2.5 and fractions predominantly between 0.63 to 1.25 mm. Coarse aggregates consisted of 20 mm crushed stone from igneous and metamorphic rocks, conforming to GOST 8267-93[6] and GOST 26633-91,[7] with a minimum crushability index of 1200. In addition, vein quartz was used for its high purity and rough surface texture, enhancing mechanical bonding. This quartz features a high specific surface area and minimal clay or organic contaminants, contributing to superior packing density and paste-aggregate adhesion.

2.1.5. Basalt Fibers

Basalt, a naturally occurring igneous rock formed from cooled volcanic lava, has gained prominence as a safer alternative to asbestos in composite reinforcement. Its transformation into fibers yields a material with excellent heat resistance and high mechanical performance. These basalt fibers are increasingly used in advanced engineering applications due to their strength, durability, and stability under extreme temperatures [33]. The basalt fibers are divided into two types, micro and macro, discussed in the following sections.

2.1.5.1. Microfibers

Basalt microfibers were utilized for early-age crack control. These fine filaments are derived from molten basalt processed at 2200°C, resulting in super thin fibers 17 μm diameter with amorphous, high-strength structures. The resultant product, known commercially as "Micro Basalt," has lengths ranging from 18.2 μm and a bulk density of 1.5–2 g/cm³. Their ultrafine nature offers excellent dispersion and a large

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[2] GOST 23732 79 (later revised as GOST 23732 2011). *Water for concrete and mortars. Technical Conditions*. Interstate Technical Committee for Standardization in Construction. 1979.

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specific surface area, ideal for mitigating plastic shrinkage and microcracking in early curing stages. They also exhibit greater chemical and thermal stability than E-glass fibers, making them suitable for aggressive environments.[8]

2.1.5.2. Macrofibers

Basalt macro fibers are coarse, elongated fibers designed to enhance post-cracking load-bearing capacity and flexural resistance. With lengths of 50 mm, diameters of 1 mm, and a tensile strength of up to 1650 MPa, these fibers provide robust crack-bridging action in hardened concrete. Their mechanical interlock with the cement matrix improves ductility and toughness, essential for pavements and slabs under dynamic loads. Their use in industrial floors, basements, and foundations underscores their utility in demanding applications. Basalt macro fibers also boast high corrosion resistance and sustainability benefits compared to synthetic alternatives.[9]

2.2. Experimental Procedure

The experimental variable central to this study was the hybridization of basalt fibers. Two categories of basalt fibers were used: microfibers and macro fibers. Micro basalt fibers, due to their fine diameters, were incorporated primarily for their ability to control early-age and plastic shrinkage cracks. In contrast, macro basalt fibers, which possess larger dimensions and higher pull-out resistance, were added to bridge wider cracks and enhance post-crack flexural performance. These fibers were combined in different ratios to form hybrid mixes, with the total fiber volume fraction kept constant across all specimens. Ratios ranged from 2:0 (pure microfibers) to 0:2 (pure macro fibers), including intermediate hybrid combinations such as 1.5:0.5, 1:1, and 0.5:1.5.

All materials were measured by weight and batched accordingly. Mixing was carried out in a pan mixer, where dry components were first blended, followed by the gradual addition of water mixed with the superplasticizer. Fibers were then slowly introduced to ensure uniform dispersion and prevent clumping. Concrete samples were cast in standard molds and compacted using a vibrating table to minimize entrapped air. The specimens were demolded after 24 hours and subjected to moist curing under controlled laboratory conditions until the testing ages of 7, 14, and 28 days.

A comprehensive suite of mechanical and durability tests was conducted to evaluate the influence of fiber hybridization. While compressive and flexural strengths were assessed according to standard procedures, additional properties were also examined to capture the broader performance profile of the fiber-reinforced concrete. These included the elastic modulus (GPa) as a measure of stiffness, and three density states—dry, saturated, and air-dried—to assess the compactness and internal cohesion of the matrix. Water absorption was measured using both air drying and oven drying cabinet methods to evaluate porosity and water permeability, while moisture content was recorded to understand residual hydration behavior and its impact on shrinkage-induced cracking.

3. Results and Discussion

The experimental procedure yielded valid results in regards to the density, stiffness and water absorption.

3.1. Densities

One of the key indicators of a well-compacted mix is the material density. In this study, three density parameters were evaluated across various hybrid fiber combinations: dry density, saturated density, and air-dried density. These metrics provide insight into the porosity, and overall compaction quality of the concrete matrix, a critical determinant of its durability and resistance to crack propagation as represented by the relationship between the values of the three different densities and the hybrid fiber combination in Figure 1.

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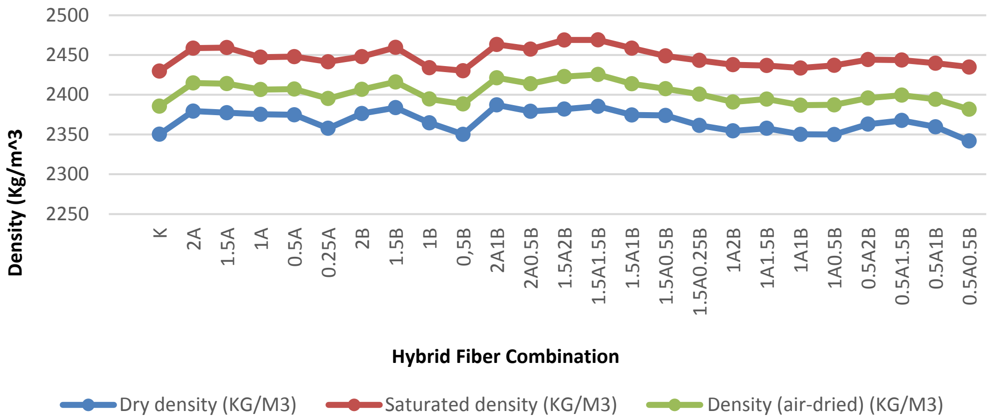

Figure 1. Varying densities against hybrid fiber combination
Source: made by Qais A.A. Qais.

The dry density of the concrete, measured after complete dehydration, revealed values ranging from 2341.85 kg/m³ to 2387.24 kg/m³. These variations indicate how fiber addition influences the packing density of the concrete. For combinations incorporating only macro basalt fibers (designated as A-series), the dry density remained relatively stable, with minor fluctuations observed across varying dosages (2A to 0.25A). This is in line with study [34], which states that due to the fact that BFs were the lightest element in the concrete mixes, there were some unit weight drops when BFs were added. This suggests that macro fibers do not significantly disrupt the packing structure of the mix, allowing for relatively uniform compaction.

In contrast, mixes containing solely microfiber reinforcement (B-series) showed a slight decrease in dry density as the fiber dosage increased, as seen in Figure 1. The lower densities observed in higher B-content mixes (e.g., 2B, 1.5B) could be attributed to the increased surface area of microfibers, which may trap more air and result in a slightly more porous matrix. Nevertheless, the overall decline in density remained marginal, indicating that the inclusion of microfibers alone does not drastically compromise compactness.

More significant effects were observed in hybrid fiber combinations, where both macro and micro basalt fibers were used in tandem. Combinations such as 2A1B, 1.5A2B, and 1.5A1.5B consistently recorded the highest density values across all three categories — dry, saturated, and air-dried. For instance, the 1.5A2B combination achieved a dry density of 2381.89 kg/m³, a saturated density of 2468.83 kg/m³, and an air-dried density of 2422.8 kg/m³. These elevated values suggest enhanced fiber interlocking and void-filling behavior, where microfibers bridge internal pores while macro fibers reinforce the matrix skeleton. This synergy appears to improve internal cohesion and reduce void content, which is crucial for resisting both micro- and macro-scale cracking.

Conversely, hybrid mixes with lower fiber contents, such as 0.5A0.5B, showed noticeably lower density values, especially in the dry and air-dried states. The reduction in density in these mixes could signal insufficient internal reinforcement and suboptimal fiber distribution, potentially increasing the susceptibility of the concrete to shrinkage, permeability, and premature cracking. The results affirm that fiber hybridization, particularly in balanced ratios (e.g., 1.5A1B, 1A1B), yields superior densification properties compared to single-scale fiber systems.

In aerodrome pavements, high-density concrete is important because it ensures that the pavement can withstand repeated aircraft wheel loads and resist external environmental impacts such as jet blast, chemical spills, and heavy rainfall. A denser concrete matrix usually has fewer pores and voids, which makes it more resistant to wear and degradation. The results showed that the addition of basalt fibers, especially in hybrid form (micro and macro), increases the density of the concrete. This improved compaction and internal packing helps the pavement maintain its strength over time. In real-world applications, this means longer service life, less surface damage, and better load transfer across joints and slabs.

3.2. Water Absorption

High water absorption generally corresponds with increased permeability, reduced durability, and susceptibility to shrinkage and cracking, especially under fluctuating environmental conditions. In this study, the water absorption behavior of concrete incorporating varying ratios of macro and micro basalt fibers was evaluated using two methods: oven-drying and air-drying. This dual approach offers insight into both laboratory-controlled and in-service environmental conditions.

Across all mixes in Figure 2, the water absorption ranged from 2.93 to 3.97% (oven-dried) and 1.65 to 2.23% (air-dried). The control sample (K) exhibited relatively high absorption (3.38 and 1.85%), reflecting the baseline porosity of conventional concrete. Interestingly, several fiber-reinforced mixes, particularly those using hybrid fiber combinations, demonstrated improved performance with slightly reduced water absorption, indicating enhanced pore refinement and improved matrix densification.

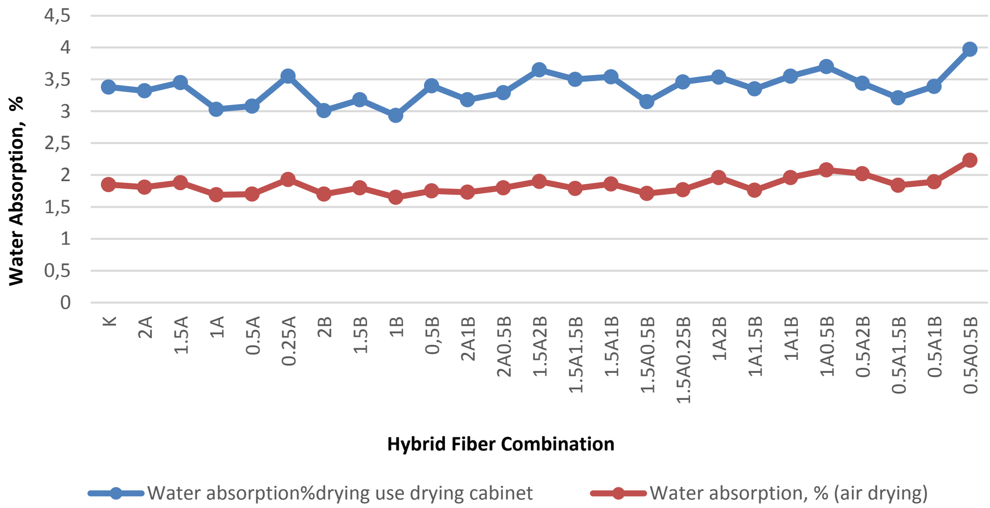

Figure 2. Water absorption (%) against hybrid fiber combination

S o u r c e: made by Qais A.A. Qais.

For mixes incorporating only macro basalt fibers (A-series), water absorption remained fairly consistent. The 1A and 0.5A combinations yielded some of the lowest values (3.03 and 3.08% for oven-dried absorption), suggesting that macro fibers may aid in reducing bulk water uptake by restricting crack development and improving internal structure. However, at very low fiber contents (e.g., 0.25A), absorption increased slightly, possibly due to insufficient bridging and ineffective crack resistance. Similarly, microfiber-only mixes (B-series) such as 2B and 1.5B maintained oven-dried water absorption below 3.2%, and air-dried values near 1.7–1.8%. Microfibers help fill voids and limit capillary networks; however, when used alone, their crack-arresting capacity for wider macrocracks is limited, possibly explaining the modest reduction in water absorption. This can also be realized from study [35], where adding 0.05% basalt fibers to self-compacting concrete reduced water absorption by 27.6%, while higher dosages (0.1%–0.2%) increased it by up to 21.2%. The reduced absorption at low content is due to improved pore structure from evenly dispersed fibers, whereas higher contents caused fiber clustering, leading to increased voids and water absorption.

The most compelling results in Figure 2 were observed in hybrid fiber combinations, especially those with balanced proportions of macro and microfibers. For instance, the 1A1B, 1.5A1B, and 2A0.5B mixes recorded some of the lowest absorption values — ranging from 3.15 to 3.29% (oven-dried) and 1.71 to 1.8% (air-dried). This suggests that the synergy between fiber scales enhances the matrix packing, limits capillary pores, and resists moisture ingress. These improvements are vital for preventing shrinkage-induced cracking and reducing freeze–thaw damage in pavement applications. Conversely, fiber blends with excessively high total fiber content, such as 0.5A2B and 0.5A1.5B, showed elevated absorption (up to 3.97 and 3.7%), likely due to poor fiber dispersion or clustering during mixing, which can introduce micro voids and weaken the homogeneity of the concrete. The highest air-dried absorption value (2.23%) was recorded for the 0.5A0.5B mix, suggesting that very low total fiber volume may be inadequate to produce meaningful improvements in moisture resistance. Low water absorption is a key requirement for airfield pavements. Water entering the concrete can cause internal cracking, freeze–thaw damage in cold climates, and accelerate deterioration due to chemicals like aviation fuel and de-icing agents. When concrete absorbs too much water, it becomes vulnerable to cracking, scaling, and corrosion of embedded materials.

3.3. Elastic Modulus (Stiffness)

In high-stress pavement environments, a higher elastic modulus is generally desirable as it contributes to greater load-bearing capacity and reduced deformation under repetitive traffic loads. However, excessive stiffness without adequate ductility can lead to brittle failure. Thus, an optimal balance is critical, particularly in fiber-reinforced concrete designed for dual crack mitigation.

In Figure 3, the elastic modulus values for 25 different mixes — including single-scale and hybrid fiber combinations — ranged from 49.3 to 53.65 GPa. The control mix (K) recorded a value of 51.5 GPa, serving as a baseline for assessing the effect of fiber inclusion on concrete stiffness.

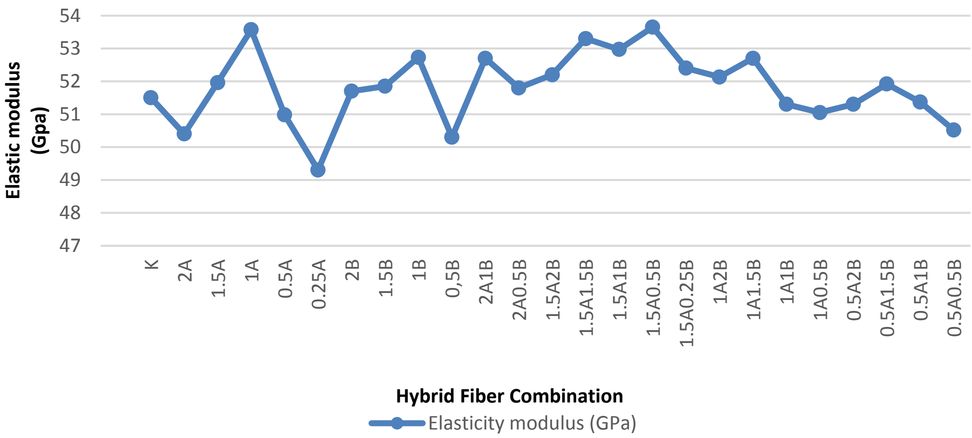

Figure 3. Elastic modulus (GPa) against hybrid fiber combination

S o u r c e: made by Qais A.A. Qais.

For the macro basalt fiber (A-series) mixes, a varied trend was observed. The 1A mix achieved the highest elastic modulus in this group (53.57 GPa), suggesting that a moderate inclusion of macro fibers improves stiffness due to their ability to restrict crack propagation and transfer stress across micro-defects. In contrast, both higher and lower fiber contents (2A, 0.5A, 0.25A) recorded lower values ranging from 49.3 to 51 GPa, indicating that suboptimal fiber ratios may reduce matrix uniformity or compromise compaction quality. This is in line with study [36], which demonstrated that the addition of basalt fibers had minimal effect on the modulus of elasticity.

The microfiber-only mixes (B-series) demonstrated moderately high elastic moduli as well, with 1B and 1.5B achieving values above 52 GPa. Microfibers, though primarily known for controlling early-age microcracking, also contribute to matrix continuity and densification, thus supporting higher stiffness values. However, very low microfiber content (e.g., 0.5B) resulted in a reduced modulus of 50.3 GPa, reinforcing the idea that microfibers alone may not sufficiently enhance load resistance in pavement concrete.

The most significant performance gains in Figure 3 were realized in the hybrid fiber combinations, particularly those with balanced macro and micro basalt fibers. Mixes such as 1.5A1.5B (53.3 GPa), 1.5A1B

(52.97 GPa), and 1.5A0.5B (53.65 GPa) recorded the highest elastic modulus values overall. This illustrates the synergistic effect of hybrid reinforcement: macrofibers resist wide crack opening and structural deformation, while microfibers fill pores and control early shrinkage, resulting in a stiffer and more crack-resistant composite. This is fairly similar to study [37], in which an experiment was conducted using different BFs ratios of 0.1–0.3% was claimed to considerably boost the modulus of elasticity. It was discovered that fiber addition increases the elastic modulus of concrete by 23% compared to the reference concrete

Notably, the 1A2B and 1A1.5B mixes also maintained high values above 52 GPa, indicating that a microfiber-dominant content can still yield strong stiffness performance when supported by a foundational macro fiber presence. Conversely, combinations with either low total fiber volume or unbalanced proportions (e.g., 0.5A0.5B at 50.52 GPa) tended to have lower stiffness, but this is in contrast with study [38], where it was found that the addition of 0.2% fiber would yield the optimum value on the stress-strain curve. The stiffness results in Figure 3 confirm that fiber hybridization is a viable pathway for enhancing structural stiffness in high-stress concrete like aerodrome pavement concrete. An optimized mix of macro–micro basalt fiber ratios yield superior mechanical synergy, increasing the ability of the aerodrome concrete to withstand loads while minimizing crack initiation and propagation. In airport pavements, this property affects how the pavement distributes aircraft loads. A pavement that is too flexible will deform excessively, leading to surface wear and rutting. On the other hand, a pavement that is too stiff may crack easily under stress.

4. Conclusion

The experimental results affirm that optimizing the ratio of micro and macro basalt fibers in concrete significantly influences key performance parameters relevant to dual-scale crack mitigation in high-stress pavement applications.

The inclusion of basalt fibers improved the concrete's resistance to both micro- and macro-cracking by enhancing its elastic modulus, densities, and reducing water absorption, which collectively support durability and dimensional stability. Hybrid fiber combinations, particularly those involving balanced proportions such as 1.5A1.5B, 1.5A0.5B, and 1.5A1B, demonstrated a consistent increase in elastic modulus (above 52 GPa), indicating improved stiffness and greater resistance to tensile-induced deformation under high stress.

These combinations promote synergistic interactions between long macro fibers (for bridging larger cracks) and short micro fibers (for dispersing micro-cracks), which is vital for pavement concrete subjected to heavy traffic loads and thermal gradients. In terms of density, hybrid fiber concretes showed higher saturated, dry, and air-dried densities compared to control mixes. This densification is indicative of improved particle packing and fiber-matrix integration, which limits porosity and enhances mechanical interlocking. The highest densities were observed in combinations like 1.5A2B and 1.5A1.5B, reinforcing the value of dual-scale fiber inclusion.

Moreover, water absorption, a key indicator of pore connectivity and durability, was notably lower in optimized hybrid mixes. For example, combinations like 1B, 1.5B, and 1.5A0.5B exhibited reduced water uptake (air-drying absorption below 1.75%), suggesting improved resistance to moisture ingress. Overall, the study demonstrates that optimized micro–macro basalt fiber ratios not only enhance the structural stiffness but also reduce permeability and improve material density, all of which are central to resisting crack initiation and propagation in pavement environments.

Recommendations:

1. Dual-scale basalt fiber reinforcement should be adopted in high-stress pavement concretes to simultaneously mitigate micro-cracking (via microfibers) and control macro-crack widening (via macro fibers).

2. Mixes within the range of 1.5A0.5B to 1.5A1.5B are recommended for their consistent performance across elastic modulus, density, and water absorption metrics. These combinations offer a strong balance between mechanical performance and durability.

3. High-density, low-absorption mixes reflect better matrix consolidation and pore refinement. These parameters should be included in quality control checks when designing fiber-reinforced pavement concrete.

4. Avoid single-scale systems for critical pavements because, while mono-fiber mixes provide some benefits, they fall short of the performance gains offered by hybrid systems, particularly in stiffness and moisture resistance.

5. Promote the use of basalt fibers in concrete mixes.

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