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Compressive Properties of Hybrid Basalt Reinforced Concrete for Aerodrome Pavement

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Abstract. Concrete remains the most widely used construction material, yet its brittleness and susceptibility to cracking limit its application in high-load structures such as aerodrome pavements. Improving mechanical strength and durability is therefore essential. While fiber reinforcement has been widely studied, mono-fiber systems often yield only partial benefits. Hybrid reinforcement using basalt macro fibers and microfibers presents a sustainable alternative, but remains underexplored, particularly for aerodrome pavements. This study investigated the influence of hybrid basalt fibers on the compressive strength of concrete at 7, 14, and 28 days, with the goal of identifying the most effective fiber proportion. Concrete mixes with different ratios of basalt macro fibers (A) and microfibers (B) were produced, cast into standard cubes, and tested for compressive strength following established guidelines. Results indicated that hybridization significantly improved strength development compared to the control. Fiber concrete mixture series achieved the highest 28-day compressive strength of 72.8 MPa, outperforming both mono-fiber and control samples. This confirms the synergistic role of hybrid fibers in enhancing crack control and load transfer. The findings suggest that hybrid basalt fiber reinforcement offers a practical, sustainable solution for high-performance concrete, with strong potential for application in aerodrome pavements and other demanding structural works.

Keywords: hybrid fibers, basalt fiber reinforced concrete, compressive strength, airfield runway, sustainable construction

Authors' contribution: *Qais Q.A.A* — laboratory experiments, writing, conceptualization, literature review, editing; *Kotlyarevskaya A.V.* — supervision, conceptualization, validation; *Okolnikova G.E.* — supervision, review and editing. All authors read and approved the final version of the article.

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Прочностные свойства гибридного базальтобетона для аэродромных покрытий

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Аннотация. Бетон остается наиболее широко используемым строительным материалом, однако его хрупкость и склонность к растрескиванию ограничивают его применение в подверженных высоким нагрузкам конструкциях, таких как покрытия аэродромов. Поэтому крайне важно повысить его механическую прочность и долговечность. Хотя армирование волокнами широко изучено, системы с одним видом волокна часто дают лишь частичные преимущества. Гибридное армирование с использованием макроволокон и микроволокон из базальта представляет собой устойчивую альтернативу, но остается недостаточно изученным, особенно для покрытий аэродромов. Авторами изучено влияние гибридных базальтовых волокон на прочность бетона на сжатие через 7, 14 и 28 дней с целью определения наиболее эффективной пропорции волокон. Были изготовлены бетонные смеси с различными соотношениями макроволокон (A) и микроволокон (B), отлиты в стандартные кубы и испытаны на прочность на сжатие в соответствии с установленными рекомендациями. Результаты показали, что гибридизация значительно улучшила развитие прочности по сравнению с контрольными образцами. Фибробетонная смесь серии 1,5A0,5B достигла наивысшей прочности на сжатие через 28 дней — 72,8 МПа, превосходя как образцы с одним видом волокон, так и контрольные образцы. Это подтверждает синергетическую роль гибридных волокон в улучшении контроля трещин и передачи нагрузки. Результаты исследования показывают, что армирование гибридными базальтовыми волокнами является практичным и устойчивым решением для высокопрочного бетона, имеющим большой потенциал для применения в аэродромных покрытиях и других сложных строительных работах.

Ключевые слова: гибридные волокна, бетон, армированный базальтовым волокном, прочность на сжатие, взлетно-посадочная полоса аэродрома, устойчивое строительство

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1. Introduction

Airport pavements are designed to withstand extremely heavy and repetitive aircraft loads while resisting environmental deterioration [1]. A key factor in their performance is the effect of impact forces from hard landings, which can accelerate structural fatigue [2]. For this reason, runway concrete is specified with high compressive strength, often between 30 and 40 MPa, and is typically reinforced with steel or other fibers to improve durability. The Federal Aviation Administration (FAA) recommends a compressive

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strength of about 4,000 psi (≈28 MPa) to achieve a 20-year runway lifespan.[1] Since compressive strength governs both load resistance and fatigue performance, higher values allow for thinner slabs or increased load capacity [3]. Recent advances have focused on lightweight high-strength concrete and ultra-high-performance concrete (UHPC), which provide enhanced durability and lower maintenance needs [4].

Basalt fibers (BFs) have emerged as a promising reinforcement for aerodrome pavements due to their high tensile strength, chemical stability, and resistance to temperature extremes. In [5], it was reported that basalt fibers improved compressive and tensile strengths by about 7%, while study [6] emphasized the influence of fiber length and dosage on workability and long-term durability. In [7], it was found that a 0.1% fiber dosage optimized compressive strength, whereas higher hybrid dosages could reduce performance. Hybridization with polypropylene further enhanced flexural behavior. In [8], it was demonstrated that basalt fiber-reinforced nano-SiO_2 concrete retained superior mechanical properties even after heating to 800°C. Similarly, study [9] showed that small fiber additions significantly improved compressive strength and salt-freezing resistance, reducing porosity and enhancing durability.

In most conventional applications, fiber-reinforced concrete (FRC) incorporates only a single fiber type. However, combining two or more fibers in suitable proportions can improve concrete's overall performance through a synergistic effect, a process referred to as hybridization [10]. In paper [11], it was demonstrated that hybrid systems significantly enhance the behavior of ultra-high-performance concrete (UHPC). For instance, the inclusion of long hooked-end steel fibers in hybrid mixes can synergistically boost compressive strength, while increasing hybrid fiber volume fraction further elevates tensile splitting strength [12]. Study [13] investigated hybrid basalt–polypropylene fiber-reinforced concrete (HBPRC) and found that hydrostatic response, peak deviatoric stress, elastic modulus, and Poisson's ratio were influenced by both confining pressure and fiber composition. Within this composite, basalt fibers primarily contribute to strength enhancement, whereas polypropylene fibers improve ductility and deformation capacity. Similarly, study [14] showed that hybridization with Kevlar and glass fibers at 1.5% dosage yielded superior compressive, flexural, and tensile strengths, along with higher toughness indices, compared to mono-fiber mixes. Concrete, derived from mineral cements, remains the most widely used construction material worldwide [15]. Its compressive capacity is traditionally evaluated through standardized cube or cylinder tests [16]. However, specimen strength is often incorrectly generalized as the material's intrinsic strength [17]. While in-situ strength measurement remains challenging [18], predictive modeling using statistical and machine learning techniques has improved accuracy and industrial relevance [19].

From a fracture mechanics standpoint, basalt fibers effectively slow crack propagation [20]. Compared with GFRP and CFRP, basalt fiber-reinforced polymer (BFRP) provides lower cost and better creep resistance [21]. For UHPC, optimal basalt fiber content of ~1% maximizes compressive, flexural, and tensile strengths [22], while also improving residual flexural performance with little difference in the damping ratio [23].

This study aims to examine the influence of hybrid basalt fiber reinforcement, combining macro fibers and microfibers, on the compressive strength of concrete for aerodrome pavements, and the objectives are to;

i. evaluate compressive strength at 7, 14, and 28 days;
ii. identify the optimal hybrid fiber mix;
iii. compare results with existing literature; and
iv. provide practical recommendations for using hybrid basalt fibers in producing durable, high-strength concrete.

Concrete is the most widely used construction material globally, yet its brittleness and cracking limit performance in aerodrome pavements exposed to high static and dynamic loads. Fiber reinforcement improves strength, but single type of fibers provides narrow benefits. Hybrid reinforcement, combining macro fibers for load transfer and microfibers for shrinkage control, offers synergistic gains, though optimal

[1] Federal Aviation Administration. AC 150/5320-6E, Airport Pavement Design and Evaluations. Washington (DC); 2009.

ratios remain underexplored. Basalt fibers, a sustainable alternative to steel or synthetics, show promise. This study investigates their hybridization to enhance pavement durability, address practical construction demands, and promote eco-friendly, high-performance concrete.

Although mono-fibers like steel, polypropylene, and glass have been widely studied, limited research exists on the combination of micro and macro basalt fibers and their effect on compressive strength across curing ages. Gaps include insufficient exploration of basalt hybridization, lack of data on optimal macro/micro ratios, dearth of specific studies relating to aircraft pavements, and practical recommendations for high-strength, durable concrete.

2. Materials and Methods

2.1. Experimental Materials

Cement. Cement is a key construction material, primarily used as a binder in concrete [24]. Portland cement comes from straightforward technology but involves complicated [25]. This study employed Portland Cement M600 CEM I 52.5, supplied by Akkermann Cement, meeting GOST 31108-2020[2] standard. Characterized by high early and ultimate strength, rapid hydration, and superior bonding, it is well-suited for high-performance and fiber-reinforced concrete.

Water. Water, though vital, is a limited resource [26]. Mixing water complied with GOST 23732-79[3], while potable water per GOST 2874-82[4] was accepted without further tests, ensuring purity, proper hydration, fiber bonding, and long-term durability.

Superplasticizer. A high-range water-reducing admixture was incorporated at 0.7% of cement weight to enhance workability at low water-to-cement ratios, improving fiber dispersion and compaction. The selected polycarboxylate-based superplasticizer effectively reduces the yield stress of the fresh mix, enabling uniform distribution of both macro- and micro-basalt fibers. This ensures optimal bonding between fibers and the cementitious matrix while preventing fiber balling or segregation, thus improving mechanical performance and surface finish quality.

Aggregates. Natural medium sands per GOST 8736-93[5], with fineness modulus 2.0–2.5 and particle sizes 0.63–1.25 mm, were supplied by OOO BATOLIT. Clean, well-graded, and free from impurities, they improved packing density, reduced voids, and enhanced workability in fiber-reinforced concrete.

Coarse aggregate was 20 mm crushed stone from igneous and metamorphic rocks, conforming to GOST 8267-93[6] and GOST 26633-91[7] standards. With crushability of not less than 1200, it provided high strength, stability, and interlock, enhancing compatibility with fibers and overall concrete performance.

Basalt Fibers (Micro and Macro). Basalt macro fibers (50 mm × 1 mm), produced from basalt rock by melt extrusion, were added to enhance toughness, crack bridging, and impact resistance. With high tensile strength and alkali resistance, they improved durability under static and dynamic loads. Basalt microfibers (18.2 mm × 17 μm) were added to control microcracks, reduce shrinkage, and strengthen the Interfacial Transition Zone. Their high aspect ratio and chemical stability enhance tensile strain capacity, long-term durability, and resistance to freeze-thaw and chemical attack.

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[2] Interstate Technical Committee for Standardization in Construction. GOST 31108-2020: Cements for general construction. Specifications. Moscow; 2020.

[3] Interstate Technical Committee for Standardization in Construction. GOST 23732-79 (rev. 2011): Water for concrete and mortars. Technical conditions. Moscow; 1979

[4] Interstate Technical Committee for Standardization in Construction. GOST 2874-82: Drinking water. Hygienic requirements and quality control. Moscow; 1982.

[5] Interstate Technical Committee for Standardization in Construction. GOST 8736-93: Sand for construction works. Specifications. Moscow; 1993.

[6] Interstate Technical Committee for Standardization in Construction. GOST 8267-93: Crushed stone and gravel of solid rocks for construction works. Specifications. Moscow; 1995.

[7] Interstate Technical Committee for Standardization in Construction. GOST 26633-91: Heavy-weight and fine concrete. Specifications. Moscow; 1991.

2.2. Experimental Procedures

Concrete mixes with basalt macro and microfibers were prepared with materials listed in Section 2. The dry materials were mixed before gradually adding water and superplasticizer to ensure uniformity and prevent fiber balling. Cubic specimens (100 × 100 × 100 mm) were cast in steel molds, compacted with vibration, and finished with a smooth steel-trowel surface. After casting, specimens were covered with a polyethylene sheet and left undisturbed for 24 ± 2 hours at laboratory temperature. Following demolding, the specimens were cured in a water tank maintained at a stable temperature, in accordance with GOST 10180-2012[8]. Specimens were cured until the designated testing ages of 7, 14, and 28 days, representing early, intermediate, and standard design strength evaluations. Compressive strength was tested using a 2000 kN machine at a controlled loading rate. Specimen ends were cleaned, centrally aligned, and loaded uniformly until failure. The maximum load at failure (*P*, in Newtons) was recorded for each specimen. The compressive strength f_c was calculated using Equation (1):

$$f_c = \frac{P}{A}, \tag{1}$$

where f_c is the compressive strength (MPa); *P* is the maximum load at failure (*N*); *A* is the cross-sectional area of the specimen (mm²).

For each mix and testing age, the average compressive strength was determined from three replicate specimens to minimize variability and improve reliability of results.

3. Results and Discussions

At seven days of curing, the compressive strength results revealed important insights into the performance of basalt macro fibers, microfibers, and their hybrid combinations in concrete. The control mix (*K*) reached 51.67 MPa in Figure 1, providing a useful baseline for comparison. When mono-fiber systems were considered, it became evident that dosage played a decisive role in determining strength outcomes.

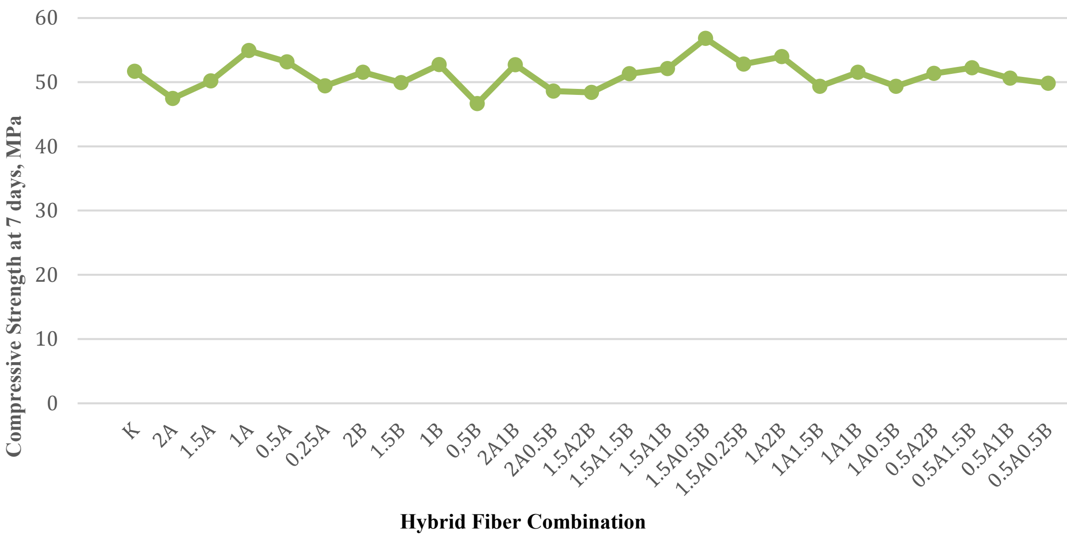

Figure 1. Compressive Strength at 7 days against Hybrid Fiber Combination
S o u r c e: made by Q.A.A. Qais.

[8] Interstate Technical Committee for Standardization in Construction. GOST 10180-2012: Concretes. Methods for strength determination using reference specimens. Moscow; 2012. (In Russ.).

For the macro fiber (A) series, strengths ranged between 47.45 and 54.90 MPa. The mix containing 1% macro fibers (1A) performed best within this group, achieving 54.90 MPa, which represented an increase of approximately 6.2% over the control. By contrast, both lower and higher dosages tended to reduce strength relative to the control, suggesting that the inclusion of macro fibers beyond the optimum level may compromise matrix consolidation and uniformity. This is similar to study [13] which stated that mono steel fiber has no significant effect on compressive strength. The compressive strength decreases when the volume fraction increases from 1.0 to 1.5%, but increases when it exceeds 1.5%. Hybrid fibers with different combination types produce a synergistic effect.

The microfiber (B) series in Figure 1 showed a similar trend, with strengths ranging from 46.66 to 52.72 MPa. The 1% microfiber mix (1B) achieved 52.72 MPa, reflecting a modest gain of about 2% over the control. However, mixes with either lower or higher microfiber contents, such as 0.5B and 1.5B, performed below the control, indicating that excessive or insufficient microfibers do not contribute positively to compressive strength. These outcomes highlight the existence of an optimum dosage range for each fiber type, beyond which workability issues, poor dispersion, or increased porosity may negatively affect structural integrity. This mirrors study [27] which compared systems with mono-fibers (steel or polypropylene) and hybrids. At 7 days, hybrid mixes had only a slight increase (from ~15.3 MPa to ~15.8 MPa) over mono-fiber ones, a small but noteworthy improvement.

The most significant improvements were observed with hybrid fiber systems, where macro fibers and microfibers were combined. The 1.5A0.5B mix recorded the highest compressive strength of 56.80 MPa as shown in Figure 1, representing a 9.9% increase over the control and outperforming all other combinations. Other hybrid mixes, such as 1A2B (53.96 MPa) and 0.5A (53.15 MPa), also displayed improvements relative to the control, although not as pronounced as the 1.5A0.5B mix. The synergistic behavior observed in these combinations suggests that moderate macro fiber content enhances load-bearing capacity while small amounts of microfibers help control microcrack propagation, leading to more efficient stress transfer and improved structural performance. Conversely, certain hybrids, such as 1.5A2B, underperformed, which indicates that high fiber volumes, particularly of microfibers, may disrupt the homogeneity of the mix, leading to reduced strength.

At 14 days of curing, the compressive strength results reflected both the continued hydration of cement and the influence of different fiber dosages and hybrid combinations. The control mix (K) achieved 58.33 MPa in Figure 2, providing the benchmark for comparison. This value illustrates the expected strength gain from the 7-day results, showing steady hydration and matrix densification.

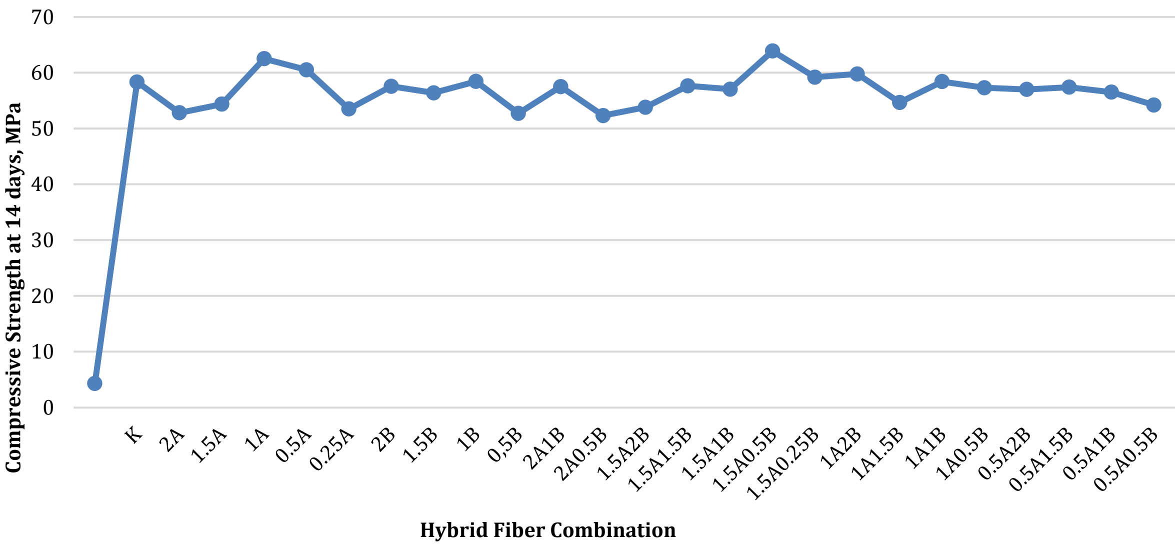

Figure 2. Compressive Strength at 14 days against Hybrid Fiber Combination
S o u r c e: made by Q.A.A. Qais.

For the macro fiber (A) series, compressive strength values ranged from 52.8 to 62.5 MPa in Figure 2. The best-performing mix was 1A, which reached 62.5 Mpa — an improvement of about 7.1% compared to the control. The 0.5A mix also performed well, achieving 60.5 MPa. These results confirm the existence of an optimum dosage window, as excessive macro fiber inclusion, such as in 1.5A and 2A, resulted in reduced strengths of 54.36 MPa and 52.8 MPa respectively. Overdosage likely led to fiber clustering, and entrapped voids, which compromise strength despite the high tensile capacity of basalt fibers.

The microfiber (B) series showed a smaller strength range, between 52.71 MPa and 58.42 MPa. The highest performance was observed in 1B, which slightly exceeded the control at 58.42 MPa, while other dosages (0.5B, 1.5B, 2B) in Figure 2 offered limited or no advantage. This indicates that microfibers contribute more effectively when combined with macro fibers rather than acting alone, as their primary role lies in controlling microcracks rather than significantly enhancing compressive resistance.

The hybrid fiber mixes produced the most significant improvements. Among these, 1.5A0.5B achieved the highest compressive strength of 63.87 MPa as illustrated in Figure 2, representing a 9.5% gain over the control and surpassing all mono-fiber mixes. Other strong performers included 1A2B (59.76 MPa) and 1.5A0.25B (59.18 MPa), both of which exceeded the control, though to a lesser degree. The synergy between macro- and microfibers appears most effective when macro fiber content is moderate and complemented by small amounts of microfibers. In such proportions, macro fibers provide crack-bridging capacity and post-cracking toughness, while microfibers limit microcrack initiation and improve the homogeneity of the cement matrix. This is slightly comparable to results from [28] which showed that the effective participation of carbon, polypropylene and steel fibers and their combination with synthetic fibers contributed positively to the performance of fiber-reinforced concrete. The gain in axial compression strength reached values in the range of 10 to 19% depending on the content of total fibers and their combination, without problems in the production process.

However, not all hybrid combinations yielded superior results. Mixes such as 1.5A2B (53.8 MPa) and 2A0.5B (52.3 MPa) underperformed, even relative to the control. These outcomes reinforce the importance of balance: high volumes of either fiber type tend to reduce compressive strength by interfering with mix compactness and increasing void content.

At 28 days, the compressive strength results clearly highlight the long-term performance of the hybrid fiber-reinforced concrete mixes, showing both continued hydration and the stabilizing effect of fiber reinforcement. The control mix (K) achieved 63.6 MPa in Figure 3, a significant improvement from its 14-day value of 58.33 MPa, demonstrating expected strength gain with curing. This benchmark provides the basis for evaluating the effectiveness of fiber additions.

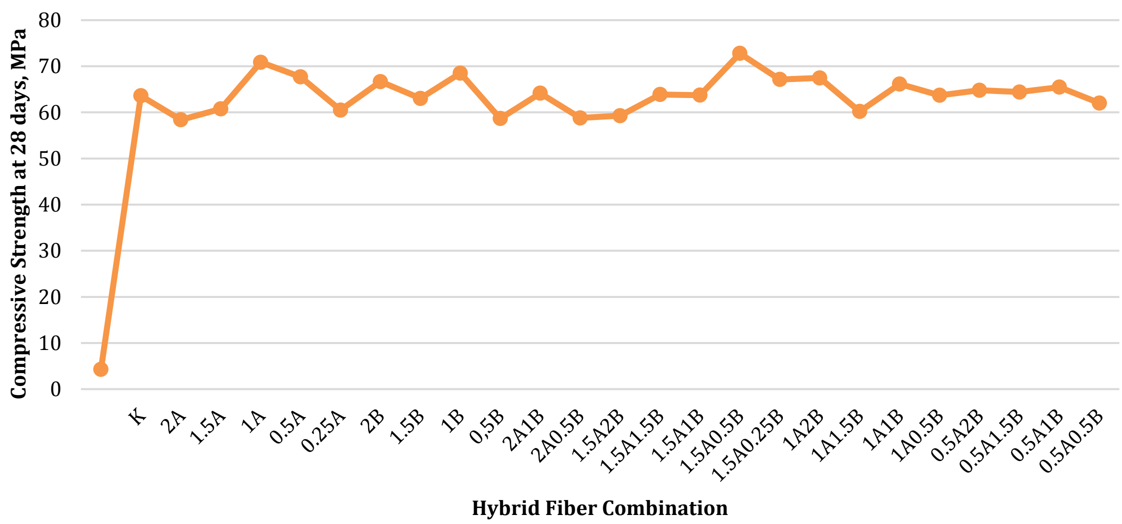

Figure 3. Compressive Strength at 28 days against Hybrid Fiber Combination
Source: made by Q.A.A. Qais.

For the macro-fiber (A) series, compressive strength ranged between 58.4 and 70.86 MPa as visualized in Figure 3. The standout mix was 1A, which achieved 70.86 MPa, representing an 11.4% improvement over the control. Similarly, 0.5A showed excellent performance with 67.7 MPa, while 1.5A and 0.25A produced moderate strengths (60.76 MPa and 60.5 MPa, respectively). The lowest performance in this group was observed in 2A (58.4 MPa), confirming the negative effects of excessive macro fiber dosage, such as poor workability, void entrapment, and fiber clustering. These results confirm that moderate macro fiber contents (0.5–1%) optimize crack-bridging without compromising mix compactness.

The microfiber (B) series generally improved compressive strength compared to the control, though less dramatically than macro fibers. In Figure 3, Strength values ranged between 58.67 and 68.5 MPa, with 1B achieving the highest strength of 68.5 MPa, surpassing the control by 7.7%. Other mixes such as 0.5B (58.67 MPa) and 1.5B (63.03 MPa) showed less improvement, while 2B (66.67 MPa) performed well. These findings suggest that microfibers are effective at enhancing long-term durability and reducing microcracking but provide more consistent rather than peak strength gains.

The hybrid fiber mixes yielded the most notable improvements, with several combinations outperforming both the control and mono-fiber mixes. The best-performing mix, 1.5A0.5B, achieved 72.8 MPa, representing a 14.5% increase over the control, highlighting strong synergy between moderate macro fibers and a small fraction of microfibers. Other effective hybrids included 1A1.5B (67.46 MPa), 1A2B (67.13 MPa), and 1A0.5B (66.16 MPa) as displayed in Figure 3. These results confirm that balancing fiber types and dosages enhances performance: macro fibers provide crack bridging and load redistribution, while microfibers improve homogeneity and limit microcrack formation. Unlike the findings of [29], where hybrid reinforcement with steel, polypropylene, and basalt fibers combined with 50% fly ash substitution achieved about a 30% increase in mechanical properties at 28 days, this study demonstrates the effectiveness of optimized basalt hybridization alone. Thus, targeted proportions of basalt macro- and microfibers can significantly improve compressive strength in high-performance concrete. Not all hybrid mixes were successful. Combinations such as 2A0.5B (58.8 MPa) and 1.5A2B (59.28 MPa) underperformed, even relative to the control, due to excessive fiber content disrupting workability and compaction. This reinforces the finding that balance, rather than quantity, trumps performance.

The compressive strength results of hybrid fiber-reinforced concrete provide a strong foundation for advancing aerodrome pavement technology. The demonstrated improvement, particularly with the 1.5A0.5B mix, shows that strategic fiber hybridization can significantly enhance both early-age and long-term structural capacity. This is critical for airfield pavements, which are subject to heavy static and dynamic loads from aircraft, as well as fatigue stresses from frequent take offs and landings. By delivering higher compressive strength, hybrid fiber mixes enable the design of thinner yet stronger pavement sections, reducing overall material consumption and construction costs while maintaining safety margins.

Furthermore, the improved strength characteristics open pathways for extending service life, minimizing maintenance needs, and reducing downtime at airports — a major economic and operational advantage. The synergy of macro- and microfibers not only enhances load-bearing capacity but also improves crack resistance, directly addressing challenges such as rutting, thermal stresses, and impact damage. These findings provide engineers with innovative material solutions that align with modern sustainability goals, allowing aerodrome infrastructure to evolve towards greater durability, resilience, and cost-efficiency while meeting the demands of increasing air traffic.

4. Conclusions

This study investigated the effect of hybrid fiber reinforcement, using basalt macro fibers (A) and microfibers (B) in varying proportions, on the compressive strength of concrete for aerodrome pavement applications. The goal was to identify optimal hybrid mixes that balance strength with workability. Experimental results across 7, 14, and 28 days revealed consistent trends. At 7 days, mix 1.5A0.5B achieved the highest strength (56.8 MPa), about 9.9% above the control, showing the early benefits of balanced hybridization. At 14 days, the same mix again led with 63.87 MPa, about 9.5% higher than the control.

By 28 days, 1.5A0.5B reached 72.8 MPa, a 14.5% improvement, confirming its long-term advantage. These findings align with recent studies highlighting that hybridization enhances strength, limits microcracking, and improves structural performance.

Recommendations:

1. For aerodrome pavements and high-strength structures, the 1.5A0.5B hybrid mix is recommended, having consistently delivered superior compressive strength across all curing ages.

2. Moderate fiber contents are essential because excessive microfibers reduce workability, hinder compaction, and compromise strength despite their crack-bridging benefits.

3. Beyond compressive strength, durability indices such as shrinkage, freeze–thaw resistance, and chloride penetration should be investigated to develop a holistic performance profile.

4. Predictive modeling can optimize fiber ratios before large-scale testing, while pilot projects in aerodrome pavements are necessary to confirm long-term field performance.

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