Hybrid Fiber-Reinforced Concrete (HFRC) For Aerodrome Pavements: Technical Feasibility And Life-Cycle Cost Analysis

Q.A.A. Qais, A.V. Kotlyarevsky, M.A.A. Obeid

RUDN University, named after Patrice Lumumba

Abstract: The scope of applying fiber-reinforced concrete in critical load-bearing structures, such as aerodrome pavements, is often limited by insufficient information regarding material behavior and life-cycle economics. This study addresses this gap by developing and evaluating an optimal hybrid mix of micro and macro-basalt fibers consisting of 1.5% and 0.5% of cement mass, respectively for high-performance airfield concrete, followed by a 30-year Life-Cycle Cost Analysis (LCCA). Mechanical testing confirmed the technical feasibility, showing significant performance gains over baseline concrete: 14.5% increase in compressive strength 72.8MPa and 18.2% increase in flexural strength 10.4MPa. These gains are attributed to enhanced durability, multi-scale crack control, and superior post-crack load-carrying capacity. The LCCA, conducted using a 6% discount rate, revealed that the hybrid option, which incurs a 13.03% higher upfront material cost, is economically viable only under the optimistic scenario where the improved durability eliminates the need for major rehabilitation over 30 years. This scenario yields a marginal LCC saving of 4% compared to the baseline. In conservative and moderate scenarios, the upfront cost outweighed the delayed or reduced rehabilitation costs. Overall, Hybrid Basalt Fiber Reinforced Concrete is a promising high-performance material that achieves cost parity if its durability benefits are maximized to prevent major rehabilitation. Future work should involve field trials and expanded LCCA incorporating operational downtime and risk-based performance modeling.

Keywords: aerodrome pavement, basalt fiber, hybrid fiber-reinforced concrete, life-cycle cost analysis, rehabilitation, discount rate, microfiber, macrofiber, net present value

1. Introduction

The range of applications for fiber-reinforced concrete is largely determined by its technical and economic advantages, which stem from the enhanced performance it offers compared to conventional concrete and concrete reinforced with steel bars [1]. Although fiber-reinforced concrete is considered a highly promising construction material, its use is most widespread in finishing works, small architectural elements, industrial floors, and decorative façade components, while its application in load-bearing structural elements remains relatively limited. This restricted use - particularly for concretes reinforced with low-modulus fibers - is mainly due to the lack of comprehensive data on how the material behaves under structural loads [2]. In the context of airport infrastructure, both flexible and rigid pavements are typically constructed to sustain aircraft movements throughout the design life of the pavement. During the planning phase, it is essential to assess the pavement structure, selected materials, expected aircraft loadings, environmental influences, and the mechanisms of pavement deterioration [3]. Basalt fibers (BF) are uniquely suited for aggressive pavement environments due to their high tensile strength, excellent corrosion resistance, and thermal stability [4]. However, single-fiber systems, whether macro or micro, are often limited in addressing crack phenomena across multiple scales. Concrete properties, including improved toughness and energy absorption, increased resistance to dynamic loads, and decreased fracture spacing and breadth, are significantly impacted by the addition of fibers to concrete [5]. Recent work has begun to explore such hybridization explicitly for aerodrome pavements. The current gap multi-scale crack control is reinforced by empirical evidence present an experimental and numerical study by [6] demonstrated that basalt fibers at low volume fractions significantly enhance compressive strength, flexural strength, and impact resistance, showcasing the potential for performance gains even with modest fiber contents.

The benefits of basalt-fiber reinforcement are not restricted to static strength. The mechanical and dynamic behavior of basalt fiber–reinforced concrete and showed that fiber addition improves residual flexural strength and increases the dynamic modulus of elasticity, critical for resisting vibrational loads such as those induced by aircraft [7]. Moreover, the durability of Basalt Fiber reinforced cementitious systems has been rigorously reviewed by [4] summarized that basalt fiber concrete exhibits enhanced resistance to freeze–thaw cycles, chloride ingress, and abrasion, all of which are relevant to airport pavements. Fig. 1 shows the samples of concrete aggregates to be reinforced through the with micro and macro basalt fibers together.

Fig.1– The aggregates for the design of the hybrid basalt fiber concrete mix

Hybrid systems that pair basalt fibers with other fiber types have also been examined. For instance, [8] studied a hybrid of basalt and polyvinyl alcohol (PVA) fibers in low-heat Portland cement concrete and reported improved fracture behavior, toughness, and crack resistance at the mesoscale, indicating that combined fiber systems may offer a balanced performance. Synthetic/steel hybrid fibers have similarly shown improved post-crack behavior, as demonstrated in high-performance fiber-reinforced concrete [9].

From a pavement-aging perspective, freeze–thaw resistance is often a limiting factor. A study by [10] on hybrid steel/basalt fiber concretes found that the presence of both fiber types significantly reduced strength loss and damage after repeated freeze–thaw cycles, compared to plain concrete. This is particularly relevant for aerodrome pavements in regions that experience cyclic freezing, where durability directly impacts life-cycle performance.

Mechanical resistance alone, though, does not guarantee economic viability. The adoption of HFRC in airfield concrete must be justified by life-cycle benefits. Traditional life-cycle cost analysis (LCCA) frameworks for airport pavement design are well established (e.g., using FAARFIELD software), showing that rigid pavements, though more expensive upfront, often yield lower life-cycle costs due to reduced rehabilitation needs [11]. In the specific context of fiber-reinforced pavement, [12] reported that hybrid fiber concrete pavements (in a real airport project) achieved up to a 20% reduction in overall maintenance costs over a 20-year life relative to non-fiber alternatives.

From an environmental and sustainability perspective, life-cycle assessments (LCA) of fiber-reinforced concretes further support their appeal. For example,

Nevertheless, the translation of lab-scale performance into enforceable field standards requires robust technical documentation: mix design protocols, quality control procedures, and acceptance testing frameworks must all be developed. This gap is highlighted in state-of-the-art reviews which call for more field trials, structured design guidance, and long-term monitoring of Hybrid Fiber-Reinforced Concrete (HFRC) in airport applications [13].

In sum, recent advances in Hybrid Basalt Fiber-Reinforced Concrete (HBFRC) suggest a compelling technical case for its use in aerodrome pavements: multi-scale reinforcement offers enhanced strength, toughness, and durability, while life-cycle studies point to possible economic and environmental advantages. Yet, to fully validate these benefits - and to translate them into practical, regulatory-ready solutions - further research is needed. This study addresses this need by; developing an optimal hybrid mix of micro- and macro-basalt fibers for airfield concrete and assessing its economic viability through a 30-year life-cycle cost analysis, bridging the gap between laboratory innovation and real-world infrastructure deployment. Fig.2 depicts micro basalt fiber samples which prevent the formation of micro cracks [14].

Fig.2– Micro Basalt Fibers

Fig.3 shows macro basalt fiber samples which are instrumental against the formation of macro cracks and increase the mechanical properties of ultra-high performance concrete (UHPC) [15].

Fig.2– Macro Basalt Fibers

The application of fiber-reinforced concretes (FRC) in critical, load-bearing structures is often limited by a lack of robust data concerning material behavior under extreme load conditions and their resulting life-cycle economics. While FRC is recognized as a promising material due to its enhanced toughness, energy absorption, and dynamic resistance, its greatest application remains in non-structural or finishing elements. This study focuses specifically on Hybrid Basalt Fiber-Reinforced Concrete (HBFRC), which leverages the high tensile strength, corrosion resistance, and thermal stability of basalt fibers to address multi-scale cracking phenomena, a significant limitation of single-fiber systems.

This study validates the performance and economic viability of Hybrid Basalt Fiber-Reinforced Concrete (HBFRC) containing micro- and macro-fibers for application in aerodrome pavements, thereby bridging the gap between laboratory innovation and field infrastructure deployment. While the objectives are to : develop an optimal hybrid mix design of micro- and macro-basalt fibers for airfield concrete and translate the laboratory findings into a comprehensive technical documentation package (including mix proportions, construction guidelines, and quality control procedures), experimentally assess the key mechanical properties (compressive and flexural strength) and durability indicators of the optimal HFRC mix relative to baseline concrete, focusing on gains in post-crack behavior and fatigue resistance and quantify the economic viability of the HFRC mix over a 30-year analysis period by performing a Net Present Value (NPV)-based LCCA, comparing the total life-cycle costs of the HFRC under various performance scenarios (Conservative, Moderate, Optimistic) against the Baseline concrete.

2. Methodology

2.1. Development of Technical Documentation and Mix Design

Laboratory findings were translated into practical technical documentation specifying:

1. mix proportions,
2. required fresh and hardened property thresholds,
3. construction and mixing guidelines,
4. quality control procedures for field acceptance.

The mix design per 1 m³ included:

1. Cement: 500 kg
2. Water: 170 kg
3. Sand: 738 kg
4. Crushed Stone: 911 kg
5. Superplasticizer: 3.5 kg (0.70% of cement mass)
6. Micro-Basalt Fibers: 7.5 kg (1.5% of cement mass)
7. Macro-Basalt Fibers: 2.5 kg (0.5% of cement mass)

Mixing protocols were adjusted to mitigate fiber clustering and ensure uniform fiber dispersion through sequence optimization and admixture adjustment.

2.2. Mechanical Testing Program

Concrete specimens were tested at 28 days for:

1. Compressive strength, using standard cylindrical compression tests;
2. Flexural strength, using third-point loading tests;
3. Workability, through slump and flow assessments;
4. Durability indicators, including crack width observation and qualitative assessment of freeze–thaw resistance.

Baseline (no fibers) samples were used for comparison.

2.3. Life-Cycle Cost Analysis (LCCA)

An economic analysis was conducted on a per-m³ basis over a 30-year period using a 6% discount rate. Cost evaluation included:

1. Initial material cost comparison between baseline concrete and HFRC.
2. Rehabilitation costs, assumed equal to 30% of baseline initial cost.

3. Three HFRC scenarios, varying rehabilitation timing and cost:

Conservative Scenario with rehabilitation delayed by 14.5% due to improved fatigue resistance, Moderate Scenario with rehabilitation cost reduced by 30% from increased durability, Optimistic Scenario with no major rehabilitation required within 30 years.

Net Present Value (NPV) calculations were performed to obtain life-cycle costs (LCC).

3. Results And Discussion

3.2. Durability and Fatigue Performance

Hybrid fibers improved the ability of the concrete to resist crack formation and propagation by:

i. reducing capillary connectivity,
ii. limiting crack widths,
iii. increasing matrix toughness, and
iv. providing superior post-crack ductility.

These characteristics translate into better resistance to:

i. freeze–thaw cycles,
ii. joint degradation,
iii. abrasion from aircraft braking,
iv. moisture/chemical ingress.

These durability benefits are especially important in cold climates and high-traffic airfields.

3.3. Workability and Constructability

Fiber addition reduced workability, as expected, due to increased internal friction and fiber–particle interactions. This was effectively mitigated through optimized superplasticizer dosage and mixing procedures. No excessive fiber balling was observed in the optimized sequence.

Fig.5 shows an example of a slump test on a Hybrid Basalt Fiber-Reinforced Concrete (HBFRC) cone sample.

Fig.3– Workability test on a Hybrid Basalt Fiber concrete

3.1. Mechanical Performance

The HFRC mix demonstrated significant performance improvements relative to baseline concrete as shown in Table 1:

Table 1

Mechanical Properties of Hybrid Basalt Fiber Concrete

Property	Baseline	HFRC	Increase
Compressive Strength	63.6 MPa	72.8 MPa	+14.5%
Flexural Strength	8.8 MPa	10.4 MPa	+18.2%

These gains indicate enhanced resistance to both internal microcracking and mechanically critical flexural stresses encountered in pavements. Improved post-crack load-carrying behavior - primarily driven by the combined action of the two fiber types - represents a major advantage for resisting slab edge deterioration under repeated aircraft loading.

Fig.4 shows a concrete sample which has been hybridized with basalt fibers, meaning it has been reinforced with micro and macro basalt fibers respectively

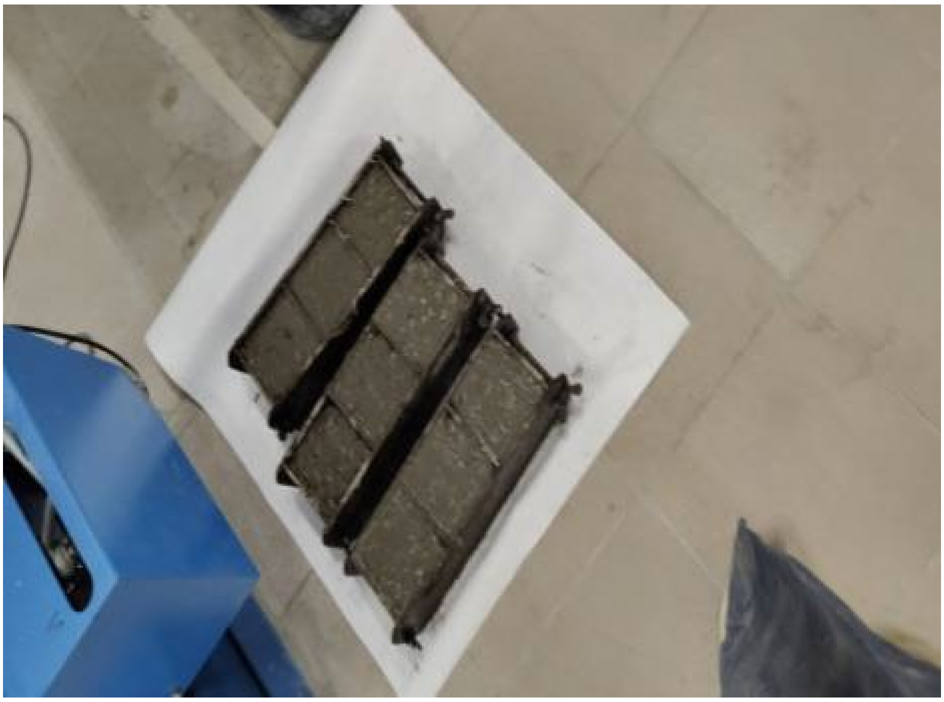

Fig.4– Hybrid Basalt Fiber Reinforced concrete casted prior to testing

3.4 Life-Cycle Cost Analysis (LCCA) of Hybrid Basalt Fiber Reinforced Concrete Pavement

3.4.1 Assumptions for the Analysis

1. All "kg/m³" mass numbers in your table are used directly (these are quantities per 1 m³ of concrete).

2. Fiber dosages (1.50% for micro basalt (A) and 0.50% for macro basalt(B) and the superplasticizer dose (0.70%) are taken as percentages of the cement mass (cement = 500 kg/m^3).
3. Unit prices (rubles/kg) are taken from the table.
4. Water (170 kg/m^3) is present but no unit price was supplied, so water cost is excluded from the monetary totals below.
5. All results are per 1 m^3 of concrete.
6. Experimental results used: 28-day compressive = 72.8 MPa and bending (flexural) = 10.4 MPa for the optimal mix 1.5A + 0.5B. Baseline (K) at 28 days: compressive = 63.6 MPa, bending = 8.8 MPa.
   i. Change in Compressive Strength = +9.2 MPa = +14.5%.
   ii. Change in Flexural Strength = +1.6 MPa = +18.2%.

Fig 6 displays a hybrid fiber reinforced concrete cube which had reached failure after being tested for compressive strength.

Fig.6– Hybrid Basalt Fiber Reinforced Concrete Cube after failure

3.4.2 Material masses (per m³) for optimal mix (1.5A, 0.5B)

1. Cement = 500 kg (given)
2. Superplasticizer = 0.70% of cement = 3.5 kg
3. Microfibers A (1.5% of cement) = 7.5 kg
4. Macro fibers B (0.5% of cement) = 2.5 kg
5. Sand = 738 kg (given)
6. Crushed stone = 911 kg (given)
7. Water = 170 kg (cost excluded)

3.4.3 Unit prices used (rub/kg)

1. Cement = 12.7
2. Superplasticizer = 95
3. Sand = 11.5
4. Crushed stone = 19
5. Macro fiber (B) = 550
6. Microfiber (A) = 381

3.4.4 Component costs (mass × unit price)

1. Cement: 500 × 12.70 = 6,350.00 rub/m³
2. Superplasticizer: 3.5 × 95 = 332.50 rub/m³
3. Sand: 738 × 11.5 = 8,487.00 rub/m³
4. Crushed stone: 911 × 19 = 17,309.00 rub/m³
5. Macro fibers (2.5 kg): 2.5 × 550 = 1,375.00 rub/m³
6. Microfibers (7.5 kg): 7.5 × 381 = 2,857.50 rub/m³

3.4.5 Totals: baseline (no fibers) and with optimal fibers

1. Baseline material cost (no fibers) = cement + superplasticizer + sand + crushed stone

= 6,350.00 + 332.50 + 8,487.00 + 17,309.00 = 32,478.50 rub/m³ (unchanged)

2. With hybrid fibers (1.5A + 0.5B) = baseline + macro fiber cost + micro fiber cost
   = 32,478.50 + 1,375.00 + 2,857.50 = 36,711.00 rub/m³
3. Incremental cost (extra for fibers) = 36,711.00 − 32,478.50 = 4,232.50 rub/m³
4. Relative increase (material cost % increase) = (4,232.50 / 32,478.50) × 100 = 13.03%

3.4.6 Fiber summary (mass & average price)

1. Compute: (component cost / total with fibers) × 100.
2. Cement: 6,350.00 / 36,711.00 = 17.30%
3. Superplasticizer: 332.50 / 36,711.00 = 0.91%
4. Sand: 8,487.00 / 36,711.00 = 23.12%
5. Crushed stone: 17,309.00 / 36,711.00 = 47.15%
6. Macro fibers (B): 1,375.00 / 36,711.00 = 3.75%
7. Micro fibers (A): 2,857.50 / 36,711.00 = 7.78%

3.5 Key Inputs and Assumptions for Life Cycle Cost Assessment

1. Analysis period: 30 years.
2. Discount rate: 6% (r = 0.06).
3. Initial (year-0) material costs (per 1 m³):
4. Baseline (no fibers) = 32,478.50 rub
5. Hybrid (1.5A + 0.5B) = 36,711.00 rub
6. Incremental upfront cost for fibers = 4,232.50 rub/m³.
7. Major rehabilitation (nominal) = 30% of baseline initial cost = 0.30 × 32,478.50 = 9,743.55 rub (this nominal cost occurs in the future at specified years).

8. Baseline rehab schedule: Year 15 and Year 30.

3.5.1 Hybrid scenarios (same definitions as before):

1. Conservative - hybrid increases material performance by 14.5% and this delays the first rehab by 14.5% (so first rehab occurs at 15×1.145 = 17.175 years). The second rehab falls outside the 30-year analysis window and is therefore not counted. Rehab cost unchanged (same nominal amount).
2. Moderate - hybrid does not change timing but reduces each major rehab cost by 30% (i.e., rehab nominal = 9,743.55 × 0.7 = 6,820.485 rub) occurring at years 15 and 30.
3. Optimistic - hybrid avoids major rehab within the 30-year horizon (no future rehab costs).

3.5.2 Net present value of future cost

For a cash flow (CF) occurring at year t, the present value is:

$$PV = \frac{CF}{(1+r)^t} \quad [16]$$

where $r = 0.06$

All LCCA totals = initial cost (year 0) + sum of PVs of future rehab costs.

Required denominators (powers of 1.06)

1. $(1.06)^{15} = 2.3965581931$
2. $(1.06)^{30}$ =5.7434911729
3. Delay factor for Conservative: $15 \times 1.145 = 17.17515$

(These powers are intermediate values used in the PV formula.)

Baseline (no fibers)

i. Nominal rehab cost (each event) = 9,743.55 rub.

Present values:

1. PV at year 15:

$$\frac{9{,}743.55}{(1.06)^{15}} = \frac{9{,}743.55}{2.3965581931} = 4{,}065.64\ rub$$

2. PV at year 30:

$$\frac{9{,}743.55}{(1.06)^{30}} = \frac{9{,}743.55}{5.7434911729} = 1{,}696.45\ rub$$

Total life-cycle cost (LCC) baseline:

$$LCC_{baseline} = PV_{15} + PV_{30} = 32{,}478.50 + 4{,}065.64 + 1{,}696.45$$
$$= 38{,}240.59\ rub/m^3$$

[17] in the Federal Highway Administration (FHWA) stated that for pavement life-cycle cost analysis, future costs must be discounted to the base year and added to initial cost to determine the Net Present Value (NPV).

3.5.3 Hybrid - Conservative (rehab delayed by 14.5%; only one rehab within 30 years)

1. First rehab time $t_1 = 15 \times 1.145 = 17.175$ years (second rehab at 34.35 years is outside the 30-year window and is not counted).
2. Same nominal rehab amount (9,743.55 rub).

Present values:

3. PV at year 15:

$$\frac{9{,}743.55}{(1.06)^{17.175}} = \frac{9{,}743.55}{2.7203716229} = 3{,}581.70\ rub$$

Total life-cycle cost (LCC) baseline:

$$LCC_{baseline} = Initial\ hybrid + PV_{t1} = 32{,}478.50 + 4{,}065.64 + 1{,}696.45 = 38{,}240.59\ rub/m^3$$

3.5.4 Hybrid - Moderate (two rehabs at years 15 & 30 but each 30% cheaper)

2. Reduced nominal rehab = $9{,}743.55 \times 0.7 = 6{,}820.485\, rub$

Present values:

3. PV at year 15:

$$\frac{6{,}820.485}{(1.06)^{15}} = \frac{6{,}820.485}{2.3965581931} = 2{,}845.95\, rub$$

4. PV at year 30:

$$\frac{6{,}820.485}{(1.06)^{30}} = \frac{6{,}820.485}{5.7434911729} = 1{,}187.52\, rub$$

Total LCC - hybrid moderate:

$$LCC_{hyb,mod} = 36{,}711.00 + 2{,}845.95 + 1{,}187.52 = 40{,}744.47\ rub/m^3$$

[18] confirmed that LCCA for pavements is commonly based on NPV methodology

3.5.5 Hybrid - Optimistic (no rehabs within 30 years)

Total LCC - hybrid optimistic:

$$LCC_{hyb,opt} = Initial\ hybrid = 36{,}711.00\ rub/m^3$$

The [19] guide on long-life pavements reiterates that LCCA uses the relationship between costs, timing of costs, and discount rates.

The HFRC only achieves cost competitiveness under the optimistic scenario, where improved durability eliminates major rehabilitation within the analysis period. In all other cases, the higher upfront material cost outweighs the savings achieved from delayed or reduced rehabilitation costs.

However, indirect benefits not included in this calculation - such as reduced runway closures, increased operational safety, and improved pavement reliability - are likely significant for airport operators and may support HFRC adoption even when direct cost advantages are marginal.

4. Conclusion

This study confirms the technical feasibility and potential economic viability of using hybrid fiber-reinforced concrete containing micro- and macro-basalt fibers for aerodrome pavements. The HFRC mix demonstrated substantial improvements in compressive and flexural strength, fatigue resistance, and durability characteristics essential for high-load pavement applications. At a 6% discount rate, the present value of future rehabilitation costs carries greater weight, making avoided or postponed rehabilitations more influential in life-cycle assessments. The life-cycle cost analysis of the hybrid concrete mix containing 1.5% micro basalt fibers (A) and 0.5% macro basalt fibers (B) shows that this combination results in a moderate increase in initial material cost but offers improved economic potential under favorable performance conditions. The inclusion of fibers raises the initial cost by 4,232.50 rubles per cubic meter, equivalent to a 13.03% increase compared to the baseline concrete.

Under optimistic assumptions, where the hybrid mix prevents major rehabilitation over the 30-year evaluation period, the life-cycle cost becomes lower than that of the baseline mix. In this scenario, the hybrid option yields a saving of about 1,529.59 rubles per cubic meter, or roughly 4%. This indicates that if the enhanced durability is realized in practice, the initial investment can be fully recovered and translated into long-term economic benefit. In contrast, under conservative and moderate assumptions, where rehabilitation is delayed or reduced but still required, the hybrid mix remains more expensive over the analysis period, increasing life-cycle costs.

Overall, the 1.5A + 0.5B configuration offers improved economic feasibility, especially when durability gains are substantial. Even when economic benefits are modest, operational advantages such as reduced downtime, greater reliability, and enhanced resistance to pavement deterioration may justify HFRC implementation in critical airfield areas. HFRC represents a promising high-performance material for demanding aerodrome infrastructure. Future work should involve large-scale field trials, long-term monitoring of performance, incorporation of HFRC behavior into pavement design standards, and expanded LCCA that includes user delay costs and risk-based performance modeling.

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