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High-Strength Lightweight Fiber-Reinforced Concrete Based on Expanded Perlite, Ceramic Brick Waste and Hybrid Fibers for Hot-Dry Climatic Conditions

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Abstract

The paper presents an experimental and analytical study of high-strength lightweight fiber-reinforced concrete designed for hot-dry climatic conditions and for the use of locally available mineral resources. The proposed composite combines CEM I 42.5N Portland cement, silica fume MK-85, limestone powder, ceramic brick waste powder, quartz sand, expanded perlite and dispersed basalt and polypropylene fibers. Expanded perlite was considered not only as a lightweight aggregate but also as a component supporting internal curing through controlled pre-wetting. Four mix variants were compared: a non-fibrous reference mixture, a basalt-fiber mixture, a polypropylene-fiber mixture and a hybrid fiber mixture. The experimental program included tests for fresh concrete workability, hardened density, compressive and flexural strength, water absorption, water tightness, frost resistance, drying shrinkage and thermal conductivity. The hybrid fiber mixture provided the most balanced result: a 28-day compressive strength of 67.9 MPa, flexural strength of 7.97 MPa, hardened density of 1512 kg/m³, shrinkage of 441 με and thermal conductivity of 0.45 W/(m·K). Regression models confirmed a positive interaction between basalt and polypropylene fibers in strength development and an additional beneficial reduction of shrinkage and thermal conductivity. The scientific novelty consists in the combined use of local expanded perlite, ceramic brick waste and hybrid fiber reinforcement to obtain a lightweight composite with high specific strength, improved crack resistance and enhanced thermal efficiency.

Keywords: Lightweight concrete, expanded perlite, ceramic brick waste, silica fume, basalt fiber, polypropylene fiber, hybrid reinforcement, shrinkage, thermal conductivity, regression modeling.

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1. Introduction

Modern construction in regions with hot-dry summers requires concretes that combine reduced self-weight, sufficient structural strength and resistance to early-age moisture loss. In north-western Uzbekistan, including Khorezm and adjacent regions, evaporation during the initial hardening period may accelerate drying shrinkage, increase the risk of surface cracking and reduce the degree of Portland cement hydration. At the same time, energy-efficient buildings require materials with lower thermal conductivity than ordinary heavy concrete. These circumstances make high-strength lightweight fiber-reinforced concrete a promising material for monolithic, precast and building-envelope elements.

The main material-science problem of lightweight concrete is the contradiction between density reduction and mechanical performance. The introduction of porous aggregates decreases the average density and thermal conductivity, but it may weaken the aggregate-matrix transition zone and increase water absorption. Therefore, the development of high-strength lightweight concrete should be based on a combined strategy: densification of the cement matrix, rational particle packing, stabilization of the water balance and crack control by fibers.

Expanded perlite is attractive for this purpose because of its low bulk density, high porosity and low thermal conductivity. When pre-wetted, perlite can act as an internal water reservoir and support delayed hydration in the cement matrix. Ceramic brick waste, after crushing and grinding, can be used as a secondary mineral resource: its powder fraction contributes to particle packing and its porous ceramic nature can influence water exchange in the composite. The use of such materials also corresponds to the principles of resource efficiency and industrial waste recycling.

Dispersed fibers are another important tool for improving the performance of lightweight concrete. Basalt fibers have a relatively high modulus and tensile strength and can bridge developing cracks under load, whereas polypropylene fibers are light, corrosion-resistant and effective against early microcracking. Their hybrid use is expected to combine different reinforcement mechanisms and to improve the balance between workability, strength, shrinkage and durability.

The aim of this study is to substantiate and experimentally evaluate a high-strength lightweight fiber-reinforced concrete based on local raw materials for hot-dry climatic conditions. The objectives are: to select the constituent materials and mix design principles; to compare the effects of basalt, polypropylene and hybrid fiber reinforcement; to evaluate mechanical, durability and thermal indicators; and to obtain regression models describing the influence of fiber components on key properties. The scientific hypothesis is that the combined action of pre-wetted expanded perlite, microfiller-based matrix densification and hybrid fiber reinforcement can provide high specific strength while limiting shrinkage and maintaining thermal efficiency.

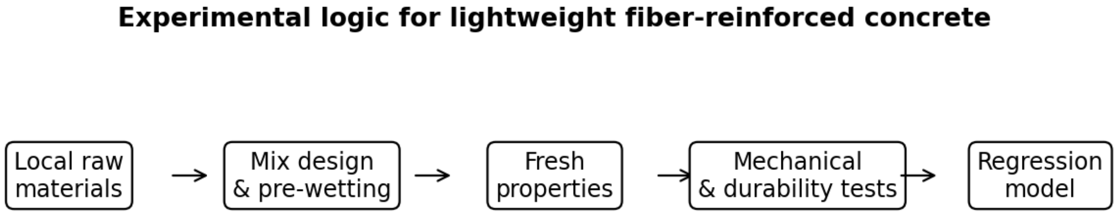

Figure 1. General experimental workflow and logic of the study.

2. Methods

2.1. Raw materials and functional roles

The raw materials were selected according to three criteria: availability in Uzbekistan, functional compatibility with high-strength lightweight concrete and ability to improve the density-strength-thermal balance. Portland cement CEM I 42.5N was used as the main binder. Silica fume MK-85 was used as an active ultrafine mineral admixture. Limestone powder and ceramic brick powder were introduced as microfillers. Expanded perlite was used as a lightweight aggregate and internal-curing component, and quartz sand formed the mineral skeleton. A polycarboxylate-based superplasticizer was used to maintain workability at a water-to-binder ratio of 0.28. Basalt and polypropylene fibers were introduced separately and in a hybrid combination.

Table 1. Raw materials used for the lightweight fiber-reinforced concrete.

Material	Main role in concrete	Selected characteristic
CEM I 42.5N Portland cement	Hydraulic binder	28-day cement strength: 55 MPa; Blaine: 350 m²/kg
Silica fume MK-85	Active pozzolanic microadmixture	SiO_2: 95.8%; average particle size: 0.15 µm
Limestone powder	Inert microfiller and rheology stabilizer	d_{50}: 18 µm; water absorption: 0.5%
Ceramic brick powder	Secondary microfiller / weak pozzolanic component	d_{50}: 45 µm; water absorption: 8%
Expanded perlite	Lightweight aggregate and internal-curing reservoir	0.16-1.25 mm; bulk density: 110 kg/m³; water absorption: up to 300%
Quartz sand	Fine aggregate	Maximum particle size: 2.5 mm; fineness modulus: 2.2
Polycarboxylate superplasticizer	Water reduction and workability control	30% solids; recommended dosage: 0.8-1.2% of binder
Basalt fiber / polypropylene fiber	Dispersed reinforcement	Length: 12 mm; hybrid use for multi-scale crack control

The expanded perlite was pre-wetted for 10-15 minutes before mixing and excess free water was removed. This operation was necessary because dry perlite can absorb a significant amount of mixing water and reduce the effective water-to-binder ratio. In the adopted approach, part of the water stored in the perlite pore system is gradually released into the cement matrix, supporting internal curing during later hydration stages.

2.2. Mix proportions and specimen preparation

Four mixtures were prepared. The reference mixture V0 did not contain fibers. Mixture V1 contained basalt fiber, mixture V2 contained polypropylene fiber and mixture V3 contained a hybrid combination of both fiber types. The binder system, aggregate content, water-to-binder ratio and superplasticizer content were kept constant to isolate the effect of fiber type and hybridization.

Table 2. Composition of the investigated lightweight fiber-reinforced concrete mixtures.

Component, kg/m³ unless noted	V_0 control	V_1 BF	V_2 PP	V_3 hybrid
Portland cement CEM I 42.5N	450	450	450	450
Silica fume MK-85	50	50	50	50
Limestone powder	60	60	60	60
Ceramic brick powder	40	40	40	40
Quartz sand	380	380	380	380
Expanded perlite	210	210	210	210
Water, L/m³	140	140	140	140
Polycarboxylate superplasticizer, L/m³	6	6	6	6
Basalt fiber	-	3.0	-	1.5
Polypropylene fiber	-	-	1.0	0.5
Water-to-binder ratio	0.28	0.28	0.28	0.28

The mixing sequence was selected to prevent clustering of ultrafine powders and fiber balling. First, cement, silica fume, limestone powder, ceramic brick powder and quartz sand were dry mixed. Then 70-80% of the water and the main part of the superplasticizer were added. Pre-wetted perlite was introduced at a reduced mixing intensity in order to avoid crushing its porous grains. Finally, fibers were added gradually and the mixture was mixed until visually uniform distribution was achieved. Specimens were cast for fresh concrete testing, compressive strength, flexural strength, shrinkage and durability assessments.

2.3. Testing methods and data processing

Fresh concrete was tested for slump and slump-flow according to the relevant concrete mixture testing procedures. Hardened density was determined on standard specimens. Compressive strength was measured at 7 and 28 days; flexural strength was measured at 28 days. Durability and service indicators included water absorption, water tightness, frost resistance, drying shrinkage and thermal conductivity. The test methods followed the logic of GOST 10181, GOST 10180, GOST 12730.1, GOST 12730.3, GOST 12730.5, GOST 10060, GOST 24544 and GOST 7076.

To quantify the contribution of the fiber system, two coded physical variables were used in regression analysis: X_1 is the basalt fiber content in kg/m³ and X_2 is the polypropylene fiber content in kg/m³. The experimental domain was X_1 = 0-3 kg/m³ and X_2 = 0-1 kg/m³. For each response Y, an interaction model of the form $Y = b_0 + b_1X_1 + b_2X_2 + b_{12}X_1 \cdot X_2$ was considered. The model is valid only within the tested composition domain and is intended for technological interpretation rather than extrapolation outside the investigated range.

3. Results And Discussion

3.1. Workability and fresh density

The workability results are shown in Table 3. The reference mixture had a slump of 245 mm and a slump-flow diameter of 717 mm. The introduction of fibers slightly decreased both indicators, but all fiber-reinforced mixtures retained high workability. The hybrid mixture V3 showed the largest decrease, with a slump of 232 mm and a slump-flow of 705 mm. This reduction is explained by the spatial fiber network, which increases internal friction and effective viscosity. Nevertheless, the decrease remained technologically acceptable and did not prevent specimen casting.

Table 3. Fresh concrete properties.

Indicator	V_0 control	V_1 BF	V_2 PP	V_3 hybrid
Slump, mm	245	237	236	232
Slump-flow, mm	717	708	707	705
Fresh density, kg/m³	1605	1615	1612	1610

The fresh density increased slightly after fiber addition, by approximately 0.3-0.6%. Since the total fiber content was low, this change is not critical for the lightweight character of the material. The main practical result is that hybrid reinforcement can be introduced without losing the high-workability condition required for reliable compaction and molding.

3.2. Compressive and flexural strength

The mechanical properties are summarized in Table 4 and Figures 2-3. At 28 days, the reference concrete reached 59.2 MPa in compression, whereas the fiber-reinforced mixtures reached 67.1-67.9 MPa. The highest value, 67.9 MPa, was obtained for the hybrid fiber mixture V3. This corresponds to an increase of 14.7% relative to the control mixture. The improvement is related to crack bridging by fibers, preservation of the effective load-bearing cross-section and the densified binder matrix formed by silica fume and microfillers.

Table 4. Hardened density and mechanical properties.

Indicator	V_0 control	V_1 BF	V_2 PP	V_3 hybrid
Hardened density, kg/m³	1510	1517	1516	1512
Compressive strength, 7 days, MPa	38.2	42.3	42.7	43.4
Compressive strength, 28 days, MPa	59.2	67.6	67.1	67.9
Flexural strength, 28 days, MPa	6.11	7.85	7.89	7.97
Specific strength $f_{c,28}/\rho$, MPa	39.2	44.6	44.3	44.9

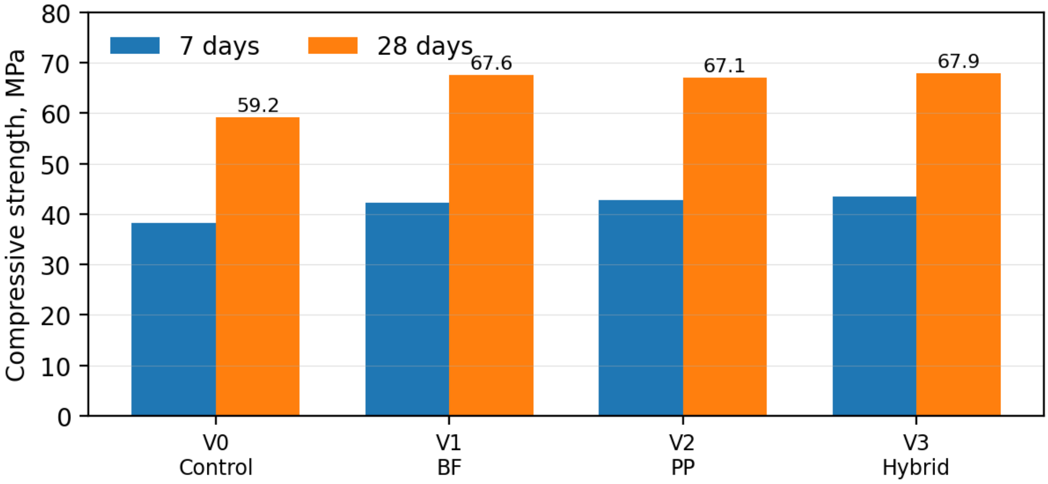

Figure 2. Compressive strength development of the investigated mixtures.

The hardened density remained within 1510-1517 kg/m³, confirming that the strength increase was not achieved by a significant increase in material density. The specific strength increased from about 39.2 MPa in the reference composition to 44.9 MPa in the hybrid composition. Therefore, the fiber system improved the strength-to-density ratio, which is one of the key criteria for high-strength lightweight concrete.

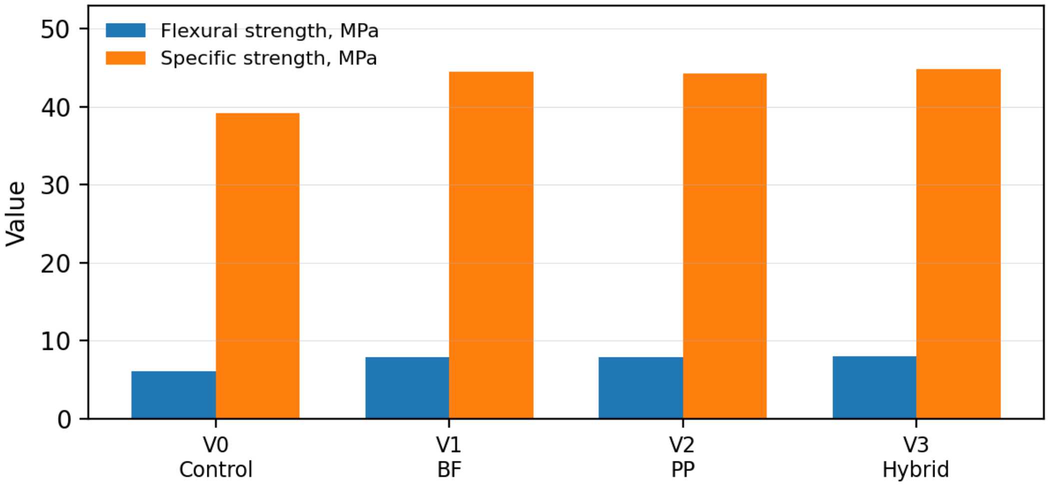

Figure 3. Flexural strength and specific compressive strength at 28 days.

The flexural strength was more sensitive to fiber addition than compressive strength. The control mixture had a flexural strength of 6.11 MPa, whereas the hybrid mixture achieved 7.97 MPa. This is a 30.4% increase. The result confirms that fibers are most effective when the composite is subjected to tensile stresses and crack opening, which is consistent with the crack-bridging mechanism. Basalt fibers are efficient due to their stiffness, while polypropylene fibers help stabilize early microcracks and reduce stress concentration. Their hybrid use provides a multi-scale reinforcement effect.

3.3. Durability, shrinkage and thermal efficiency

The durability and service-performance indicators are presented in Table 5. Fiber-reinforced mixtures showed lower water absorption, higher water tightness and higher frost-resistance grade than the reference composition. The hybrid mixture reached W20 water tightness and F800 frost resistance, while water absorption did not exceed 6% by mass. These results indicate that the fiber system and dense matrix reduced the continuity of capillary pores and limited the formation of connected microcracks.

Table 5. Durability, shrinkage and thermal indicators.

Indicator	V_0 control	V_1 BF	V_2 PP	V_3 hybrid
Water absorption, mass %	<=7	<=6	<=6	<=6
Water tightness grade	W18	W20	W20	W20
Frost resistance grade	F700	F800	F800	F800
28-day shrinkage, με	462	448	445	441
Thermal conductivity, W/(m·K)	0.51	0.48	0.47	0.45

Drying shrinkage decreased from 462 με in the reference mixture to 441 με in the hybrid mixture. This reduction is attributed to three factors: internal curing through pre-wetted expanded perlite, crack-bridging by fibers and a denser cement matrix formed by the ultrafine silica fume and microfillers. The result is especially important for hot-dry climates, where surface evaporation can rapidly increase early tensile stresses in concrete.

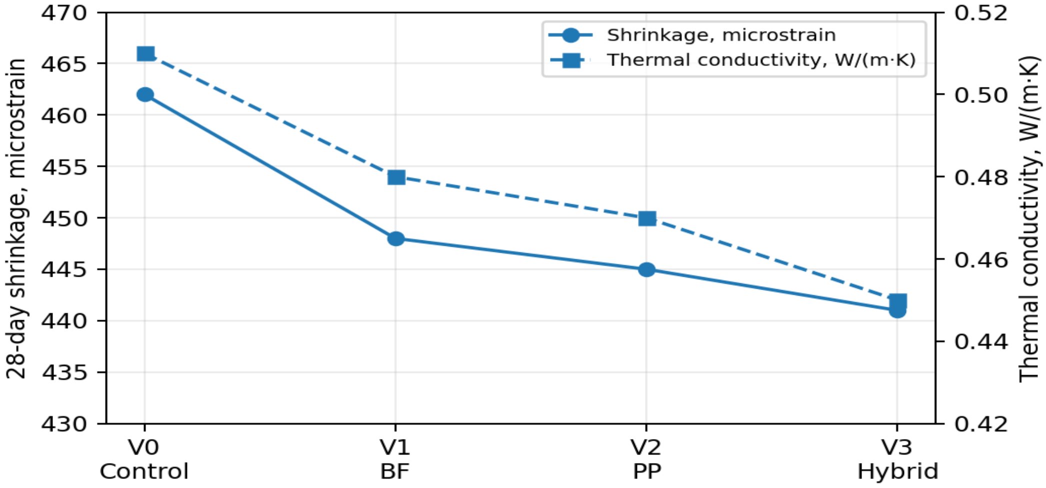

Figure 4. Change in drying shrinkage and thermal conductivity depending on reinforcement type.

Thermal conductivity decreased from 0.51 W/(m·K) in the reference composition to 0.45 W/(m·K) in the hybrid composition. The main reason is the presence of expanded perlite, which forms a low-density porous mineral component. The additional reduction in fiber-reinforced variants may be related to microcrack control and more uniform pore distribution. The combination of high compressive strength and low thermal conductivity is relevant for structural elements where both load-bearing and energy-saving functions are required.

3.4. Regression modeling and interpretation of hybrid synergy

Regression coefficients are shown in Table 6. Positive coefficients b_1 and b_2 in the compressive and flexural strength models indicate that both basalt and polypropylene fibers contribute to strength development. The positive interaction coefficient b_{12} confirms that the hybrid combination provides an additional strengthening effect beyond the separate linear contributions. For shrinkage and thermal conductivity, the negative coefficients are beneficial because the target is to reduce these indicators.

Table 6. Interaction regression model coefficients for X_1 = basalt fiber and X_2 = polypropylene fiber.

Response Y	b_0	b_1	b_2	b_{12}
$Y_1 = f_{c,28}$, MPa	59.20	2.80	7.90	0.73
Y_2 = flexural strength, MPa	6.11	0.58	1.78	0.13
Y_3 = shrinkage, με	462.00	-4.67	-17.00	-7.33
Y_4 = thermal conductivity, W/(m·K)	0.5100	-0.0100	-0.0400	-0.0333

Y_5 = slump, mm	245.00	-2.67	-9.00	-6.00

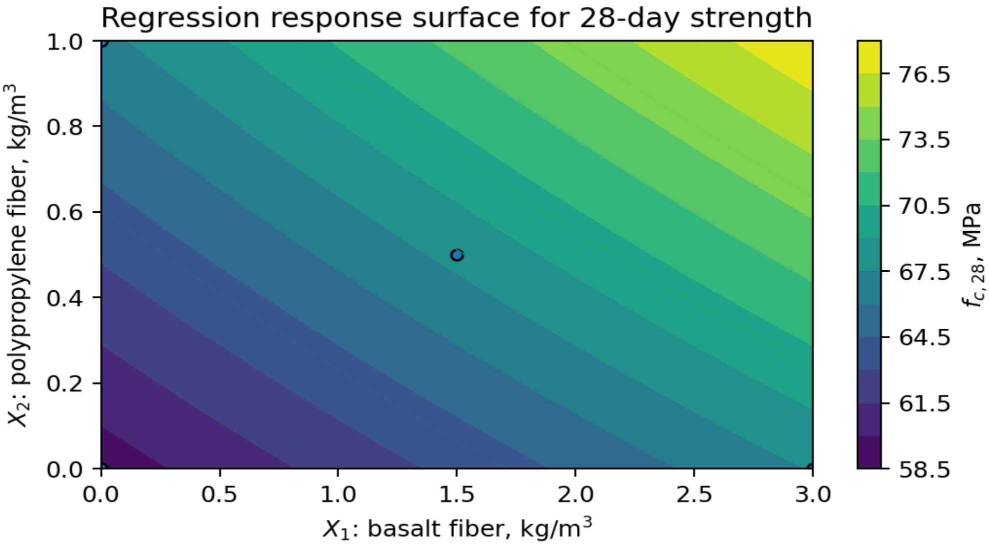

Figure 5. Response surface for 28-day compressive strength within the investigated fiber-content domain.

For the hybrid mixture, the model predicts fc,28 = 59.20 + 2.80·1.5 + 7.90·0.5 + 0.73·1.5·0.5 = 67.9 MPa, which coincides with the experimental value. The same approach gives a flexural strength close to 7.97 MPa, shrinkage close to 441 με and thermal conductivity close to 0.45 W/(m·K). Thus, the regression model adequately reflects the observed experimental trends and can be used for preliminary optimization of fiber proportions in the studied range.

The interaction effect is physically meaningful. Basalt fibers, due to their stiffness, increase the resistance of the matrix to crack opening under load. Polypropylene fibers, due to their lower modulus and better distribution in the fresh mixture, stabilize early microdefects and reduce the probability of their transformation into larger cracks. When both types are used together, the composite receives reinforcement at different deformation stages. However, the model also shows a negative effect on slump, which means that technological optimization of mixing sequence and superplasticizer dosage is necessary when hybrid fibers are used in larger amounts.

4. Conclusions

1. A high-strength lightweight fiber-reinforced concrete suitable for hot-dry climatic conditions was developed using local and secondary mineral resources: expanded perlite, ceramic brick waste powder, silica fume, limestone powder, quartz sand and hybrid basalt-polypropylene fiber reinforcement.
2. The use of expanded perlite reduced density and thermal conductivity, while pre-wetting provided an internal-curing mechanism that contributed to lower drying shrinkage. This mechanism is valuable for regions where early-age moisture loss is intense.
3. Fiber addition did not critically impair workability. The hybrid mixture retained a slump of 232 mm and a slump-flow of 705 mm, which is sufficient for technological placing and compaction in the tested system.
4. The hybrid fiber mixture showed the best balance of properties: density 1512 kg/m³, compressive strength 67.9 MPa, flexural strength 7.97 MPa, water tightness W20, frost resistance F800, shrinkage 441 με and thermal conductivity 0.45 W/(m·K).
5. Regression modeling confirmed a positive interaction between basalt and polypropylene fibers for strength indicators and a beneficial interaction for reducing shrinkage and thermal conductivity. Therefore, hybrid reinforcement is more effective than a single-fiber approach when the objective is to obtain a balanced structural and thermal performance.
6. The proposed composite can be recommended for further pilot-scale verification in precast and monolithic elements where low self-weight, high specific strength, crack resistance and energy efficiency are required.

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