

Moisture-Balanced Design of Expanded-Perlite and Ceramic-Waste Lightweight Concrete for Hot-Dry Climatic Conditions

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Abstract

This paper presents a separate material-design study focused on moisture balance, internal curing potential and resource-efficient raw-material selection for structural lightweight concrete intended for hot-dry climatic conditions. Unlike a conventional strength-centred comparison of fiber systems, the present work evaluates the technological role of expanded perlite, crushed ceramic brick waste, ceramic brick powder, limestone powder and silica fume in a low water-to-binder cementitious system. The study uses locally available mineral resources: CEM I 42.5N Portland cement, MK-85 silica fume, limestone powder, ceramic brick powder, quartz sand, crushed ceramic brick aggregate and pre-wetted expanded perlite. A moisture-balance approach was applied to estimate the potential internal water reservoir of porous components, and performance indices were calculated from the achieved properties of the optimized mixture. The designed concrete reached a slump of 16.5 cm, slump-flow diameter of 595 mm, average density of 1605 kg/m³, 28-day compressive strength of 57.0 MPa, flexural strength of 7.50 MPa, 28-day drying shrinkage of 0.475 mm/m and thermal conductivity of 0.475 W/(m·K). The calculated specific compressive strength was 35.5 MPa, while the strength-to-conductivity index reached 120 MPa·m·K/W. The results show that pre-wetted expanded perlite and ceramic waste components can be combined not only to reduce density and improve thermal efficiency, but also to stabilize the water balance of the cement matrix during early hydration in dry environments.

Keywords: Expanded perlite, ceramic brick waste, internal curing, lightweight concrete, moisture balance, hot-dry climate, silica fume, thermal efficiency.

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1. Introduction

The development of structural lightweight concrete for hot-dry regions requires a design strategy that differs from the ordinary approach used for dense concrete. In such environments, intensive evaporation during the first hours and days after casting may interrupt hydration, increase capillary porosity and intensify shrinkage. For north-western regions of Uzbekistan, including Khorezm, this problem is especially important because summer construction is commonly performed under low relative humidity and high surface drying rates. Consequently, the material must combine adequate flowability, high specific strength, reduced thermal conductivity and dimensional stability.

A promising way to solve this problem is to use porous mineral components that perform two functions at the same time. First, lightweight porous aggregates decrease the density of the composite and improve thermal performance. Second, if they are pre-wetted before mixing, part of the absorbed water is retained in the pore structure and can be gradually released during hydration. This mechanism is usually described as internal curing. It is particularly useful when external curing is difficult to maintain or when the concrete surface is exposed to early drying.

Expanded perlite is a suitable internal-curing and lightweight component due to its very low bulk density and high absorption capacity. However, perlite grains are mechanically fragile, and careless mixing can crush

them, increase the amount of fine particles and alter the intended mixture design. Therefore, the technological sequence of mixing and the moisture state of perlite must be controlled. At the same time, the use of ceramic brick waste as aggregate and powder offers an additional resource-saving direction. Ceramic waste is available from brick production, and its aluminosilicate nature may contribute to matrix packing and partial secondary activity when finely ground.

The scientific novelty of this paper lies in considering expanded perlite and ceramic brick waste primarily as a moisture-management and packing system rather than only as density-reducing fillers. The aim is to substantiate the raw-material design, calculate the internal water-reservoir potential of porous components and evaluate the resulting thermo-structural performance indices of the optimized lightweight concrete.

2. Methods

2.1. Binder and mineral components

The binder system was based on CEM I 42.5N Portland cement. The cement was selected because it provides a reliable early and 28-day strength level and is compatible with low water-to-binder mixtures modified by a polycarboxylate superplasticizer. The main cement characteristics are summarized in Table 1. The 28-day cement strength of 55 MPa confirms that the binder has sufficient potential for structural lightweight concrete.

Table 1. Main characteristics of CEM I 42.5N Portland cement used in the study.

Property	Unit	Value
True density	kg/m ³	3100
Bulk density	kg/m ³	1100
Blaine fineness	m ² /kg	350
Normal consistency	%	27.5
Initial setting time	min	150
Final setting time	min	240
Le Chatelier expansion	mm	1.0
Compressive strength at 2 days	MPa	25.0
Compressive strength at 28 days	MPa	55.0

The fine mineral system consisted of silica fume, limestone powder and ceramic brick powder. Silica fume was used as an active pozzolanic microadmixture with a high content of amorphous SiO₂. Limestone powder was used mainly as an inert microfiller and rheology

stabilizer, while ceramic brick powder was treated as a secondary aluminosilicate powder capable of improving particle packing and contributing to resource efficiency. The main functional roles of the selected materials are given in Table 2.

Table 2. Functional roles and selected characteristics of mineral components.

Material	Functional role	Selected characteristic
Silica fume MK-85	Active ultrafine pozzolan	SiO ₂ = 95.8%; d _{mean} = 0.15 μm; surface area about 18000 m ² /kg

Limestone powder	Inert microfiller and rheology stabilizer	$d_{50} = 18 \mu\text{m}$; true density = 2700 kg/m ³ ; water absorption = 0.5%
Ceramic brick powder	Secondary aluminosilicate microfiller	$d_{50} = 45 \mu\text{m}$; true density = 2550 kg/m ³ ; water absorption = 8.0%
Expanded perlite	Lightweight aggregate and internal-curing reservoir	0.16-1.25 mm; dry bulk density = 110 kg/m ³ ; water absorption up to 300%
Crushed ceramic brick aggregate	Porous secondary aggregate	0.63-5 mm; bulk density = 850-900 kg/m ³ ; water absorption = 10.5-12.0%
Quartz sand	Fine aggregate skeleton	0-2.5 mm; fineness modulus = 2.2; water absorption = 1.2%
PCE superplasticizer	Water reduction and workability retention	30% solids; recommended dosage 0.8-1.2% of binder

2.2. Mixture design concept and moisture-balance calculations

The mixture design was organized around three linked principles: (i) a low water-to-binder ratio to obtain high matrix strength, (ii) a combined granular skeleton formed by quartz sand and crushed ceramic brick aggregate, and

(iii) an internal-curing reservoir produced by pre-wetted expanded perlite. The component distribution by function is shown in Table 3. The table is presented as a functional design rather than as a fiber-comparison matrix, because the present article focuses on water balance and material selection.

Table 3. Functional composition of the proposed moisture-balanced lightweight concrete.

Functional group	Component	Dosage	Purpose
Binder	Portland cement + silica fume	450 + 50 kg/m ³	Hydration and high-strength matrix
Microfiller package	Limestone powder + ceramic brick powder	60 + 40 kg/m ³	Packing of fine pores and contact-zone densification
Fine aggregate	Quartz sand	450 kg/m ³	Dimensional stability and granular skeleton
Secondary porous aggregate	Crushed ceramic brick 0.63-5 mm	350 kg/m ³	Lower density and resource efficiency
Internal-curing lightweight aggregate	Pre-wetted expanded perlite	70 kg/m ³ dry mass	Water storage and reduction of early moisture loss
Chemical admixture	PCE superplasticizer	6.0 kg/m ³	Low W/B at workable consistency

To quantify the internal water-reservoir potential, the maximum water absorption capacity of each porous component was estimated using Eq. (1):

$$W_{cap} = m_i \cdot A_i / 100, \tag{1}$$

where W_{cap} is the calculated water capacity of component i , kg/m³; m_i is the dry mass of the component

in the mixture, kg/m³; and A_i is its water absorption, % by mass. This calculation does not assume that all absorbed water is immediately available for hydration. Instead, it gives an upper material capacity and helps compare the relative contribution of each component to the water balance.

Table 4. Calculated potential water capacity of porous mineral components.

Component	Dry mass, kg/m ³	Absorption, %	Calculated capacity, kg/m ³
Expanded perlite	70	300.00	210.00
Ceramic aggregate	350	11.25	39.38
Ceramic brick powder	40	8.00	3.20
Quartz sand	450	1.20	5.40
Limestone powder	60	0.50	0.30

The physical performance of the designed mixture was evaluated by conventional indicators: workability, density, compressive strength, flexural strength, shrinkage and thermal conductivity. In addition, derived indices were calculated to interpret the balance between structural and thermal efficiency. The specific compressive strength was calculated as $f_{c,28} / \text{prel}$, where prel is density divided by the density of water. The

strength-to-conductivity index was calculated as $f_{c,28} / \lambda$, and the thermo-structural index as $f_{c,28} / (\text{prel} \cdot \lambda)$. These indices are useful when lightweight concrete is intended not only to carry load but also to reduce heat transfer through the envelope or structural element.

2.3. Preparation sequence and testing methods

The dry powders and normal aggregates were first homogenized to prevent local concentration of silica

fume and ceramic brick powder. Water containing the polycarboxylate superplasticizer was then added in stages. Expanded perlite was pre-wetted for 10-15 minutes and introduced after the initial paste had formed; this sequence reduces perlite crushing and prevents dry

perlite from withdrawing too much free water from the cement paste. If fibers are used in a technological variant, they should be added gradually after the paste has coated the aggregates, because sudden addition can cause balling.

Table 5. Experimental methods used for validation of the material design.

Measured property	Methodological principle	Standard / procedure
Workability	Slump and slump-flow	GOST 10181-2014 or equivalent fresh concrete procedure
Density	Mass-to-volume measurement	GOST 12730.1
Compressive strength	Standard cube specimens	GOST 10180-2012
Flexural strength	Prismatic specimens under bending	GOST 310.4 / equivalent concrete bending procedure
Shrinkage	Length change of prism specimens	GOST 24544-2020
Thermal conductivity	Steady-state heat-flow method	GOST 7076-99
Water quality	Mixing water control	GOST 23732-2011

3. Results And Discussion

3.1. Raw-material suitability for hot-dry concrete technology

The cement properties in Table 1 show that the selected binder provides sufficient early strength and a normal technological setting window. The initial setting time of 150 minutes and final setting time of 240 minutes are compatible with batching, transportation and placing operations in laboratory conditions. For hot-dry construction, this is important because excessively fast setting may intensify plastic shrinkage, while excessively

slow setting may increase the period during which the surface remains vulnerable to drying.

The fine-particle system is also important. Silica fume improves the density of the cement stone through a microfilling effect and pozzolanic reaction. Limestone powder improves particle packing and can reduce the amount of paste required to fill voids between larger grains. Ceramic brick powder is more porous and more water-absorptive than limestone powder, but its secondary origin makes it attractive for sustainable material design. The combined use of these powders allows the system to balance activity, packing and resource efficiency.

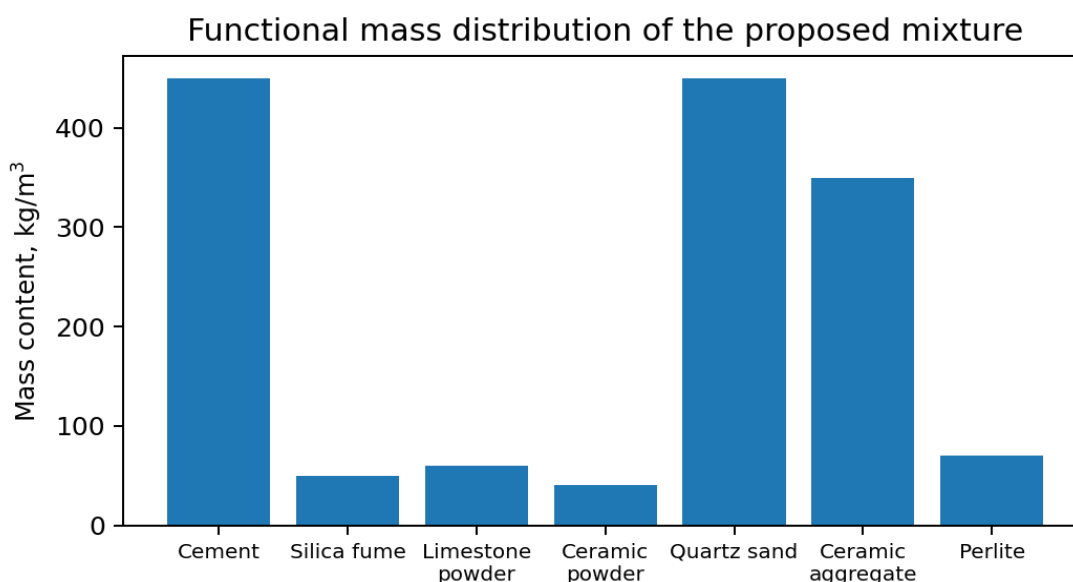


Figure 1. Functional mass distribution of the proposed mixture.

Figure 1 illustrates that the mixture is not dominated by a single component. The binder content is high enough

to create a continuous strong matrix, while quartz sand and ceramic aggregate provide the main granular

skeleton. Expanded perlite has a relatively low mass content because of its very low density, yet it has a disproportionately large functional role in thermal performance and moisture storage.

3.2. Moisture-reservoir function of expanded perlite and ceramic waste

The most important distinction between the selected components is their water absorption. Figure 2 shows

that expanded perlite has a substantially higher absorption capacity than the other mineral materials. This property explains why the perlite moisture state must be controlled before mixing. If dry perlite is added directly, it may absorb a large part of the mixing water and reduce workability. If it is pre-wetted and excess free water is removed, it can function as an internal water reservoir.

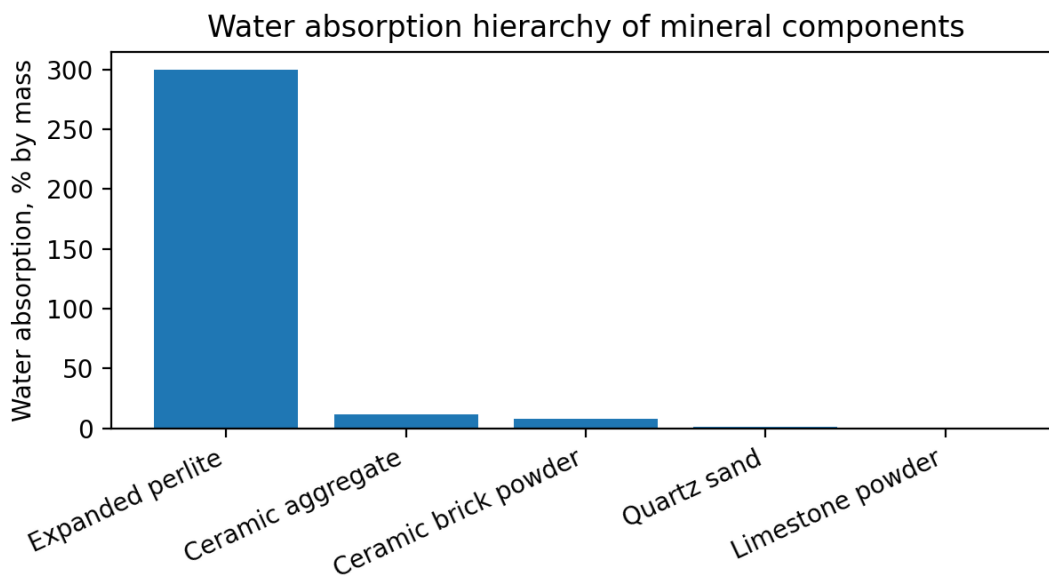


Figure 2. Water absorption hierarchy of selected mineral components.

The calculated water-reservoir capacities in Table 4 and Figure 3 demonstrate that 70 kg/m³ of expanded perlite can theoretically hold up to 210 kg/m³ of water at maximum absorption. This value is larger than the total mixing water of the designed composition and therefore should not be interpreted as the amount of water

intentionally introduced. It indicates the capacity reserve of the material. In practical concrete production, only a controlled part of this capacity should be used so that perlite grains are close to a stable pre-wetted state and do not disturb the effective water-to-binder ratio.

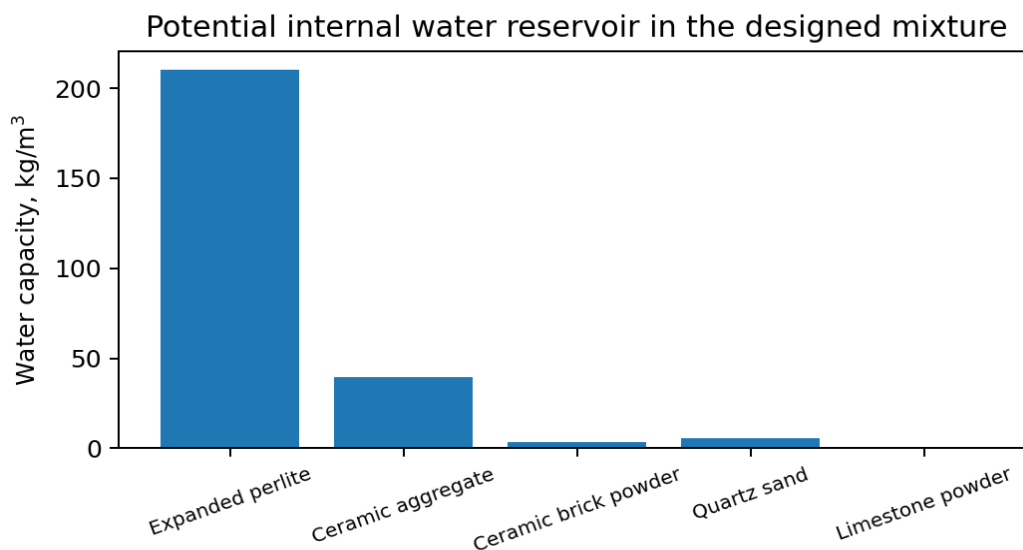


Figure 3. Potential internal water reservoir calculated from material absorption and dosage.

Crushed ceramic aggregate also contributes to water balance, but its effect is much smaller than that of perlite. At an average absorption of 11.25%, 350 kg/m³ of ceramic aggregate can hold about 39.4 kg/m³ of water. Ceramic brick powder and quartz sand have much lower capacities. This hierarchy supports a two-level concept: expanded perlite acts as the main internal-curing reservoir, while ceramic aggregate provides a secondary reservoir and a resource-efficient porous skeleton. The use of both components is therefore more rational than relying on only one porous material.

3.3. Achieved technological and performance indicators

The technological and performance indicators of the optimized moisture-balanced mixture are summarized in Table 6. The slump of 16.5 cm and slump-flow diameter of 595 mm show that sufficient workability was retained despite the presence of porous aggregates and ultrafine powders. The average density of 1605 kg/m³ places the material in the structural lightweight concrete range while maintaining a 28-day compressive strength of 57.0 MPa.

Table 6. Achieved properties of the optimized moisture-balanced lightweight concrete.

Indicator	Unit	Value	Interpretation
Slump	cm	16.50	fresh mixture workability
Slump-flow diameter	mm	595	flowability under low W/B
Average density	kg/m ³	1605	lightweight structural range
Compressive strength, 7 days	MPa	40.00	early strength
Compressive strength, 28 days	MPa	57.00	structural strength
Flexural strength, 28 days	MPa	7.500	crack-resistance indicator
Drying shrinkage, 28 days	mm/m	0.475	dimensional stability
Thermal conductivity	W/(m·K)	0.475	thermal efficiency

The 7-day compressive strength reached 40.0 MPa, corresponding to approximately 70% of the 28-day strength. This ratio indicates that the cement-silica fume matrix develops sufficiently fast strength even under the low W/B condition. The flexural strength of 7.50 MPa is also high for a lightweight system and confirms that the granular skeleton and microfilled matrix provide resistance to crack initiation. The drying shrinkage of 0.475 mm/m is moderate considering the low W/B ratio and the presence of high-surface-area materials. The result supports the hypothesis that pre-wetted porous

components can reduce early water deficiency and contribute to dimensional stability.

3.4. Thermo-structural performance indices

A single property is not sufficient to evaluate structural lightweight concrete for hot-dry climates. A material with high strength but high thermal conductivity may not be energy-efficient, while a very light thermal insulation material may not carry structural load. Therefore, derived indices were calculated from the achieved properties. They are presented in Table 7 and visualized in Figure 4.

Table 7. Derived performance indices for the optimized mixture.

Index	Formula	Value	Unit
Relative density	$\rho/1000$	1.605	dimensionless
Specific compressive strength	$f_{c,28} / \rho_{rel}$	35.51	MPa
Early-strength coefficient	$f_{c,7} / f_{c,28}$	0.7018	ratio
Flexural-to-compressive ratio	$f_{flex} / f_{c,28}$	0.1316	ratio
Strength-to-conductivity index	$f_{c,28} / \lambda$	120.00	MPa·m·K/W
Specific thermo-structural index	$f_{c,28} / (\rho_{rel} \cdot \lambda)$	74.77	MPa·m·K/W
Shrinkage per unit strength	$\epsilon_{sh} / f_{c,28}$	0.0083	mm/m per MPa

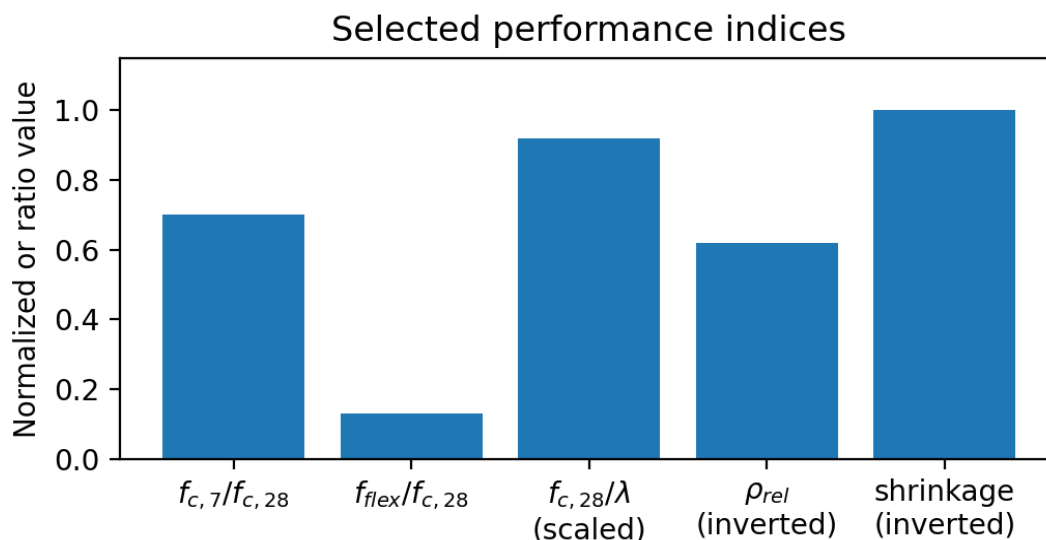


Figure 4. Selected normalized and ratio-based performance indices.

The specific compressive strength of 35.5 MPa confirms that the material is not only strong in absolute terms but also efficient relative to its density. The strength-to-conductivity index of 120 MPa·m·K/W shows that the mixture has a favourable combination of mechanical and thermal properties. The thermo-structural index, which also accounts for density, reached 74.7 MPa·m·K/W. These values demonstrate that the design is suitable for elements in which reduced self-weight and improved thermal behaviour are both important.

The flexural-to-compressive ratio of 0.1316 is higher than that typical of many ordinary brittle cement composites. This suggests that the material has an improved ability to resist bending and crack initiation, which is important in thin-walled and precast elements. The shrinkage per unit strength was 0.0083 mm/m per MPa, indicating that the achieved strength was not accompanied by excessive drying deformation. This is a key advantage for hot-dry climates, where shrinkage cracking frequently limits service life.

3.5. Practical implications for production technology

The results lead to several practical recommendations. First, expanded perlite should not be treated as an ordinary dry aggregate. It must be pre-wetted under controlled conditions, and excess free water should be removed before dosing. Second, the sequence of mixing is crucial. Dry blending of cement, silica fume, limestone powder, ceramic powder and quartz sand should precede the addition of the main mixing water and superplasticizer. Perlite should be added later to reduce mechanical damage to its porous grains.

Third, ceramic brick waste can be used in two forms: as a powder and as a crushed aggregate. The powder improves the fine-particle packing of the cementitious matrix, while the aggregate reduces density and supports the moisture-buffering mechanism. Fourth, the effective water-to-binder ratio should be distinguished from the total water introduced into the system. Part of the water can be temporarily stored in porous aggregates and should be considered as internal-curing water rather than as ordinary free mixing water.

From an environmental and economic point of view, the use of ceramic brick waste reduces the need for natural mineral aggregates and provides a recycling pathway for local production waste. The technological risk associated with this approach is the variability of waste material. Therefore, particle size distribution, water absorption and dust content must be monitored for each batch. If these parameters are controlled, ceramic waste can become a stable component of structural lightweight concrete.

4. Conclusions

1. A moisture-balanced lightweight concrete design was scientifically substantiated using CEM I 42.5N cement, silica fume, limestone powder, ceramic brick powder, crushed ceramic brick aggregate and pre-wetted expanded perlite. The article focused on water balance and raw-material function, which makes it distinct from a conventional fiber-comparison study.

2. Expanded perlite showed the highest water absorption capacity among the selected components. At 70 kg/m³

dry dosage and 300% absorption, its maximum theoretical water capacity is about 210 kg/m³. This confirms its potential as an internal-curing reservoir, provided that pre-wetting is controlled and excess free water is removed.

3. Crushed ceramic brick aggregate and ceramic brick powder provide a secondary moisture-buffering effect and improve resource efficiency. The aggregate contributes about 39 kg/m³ of potential water capacity, while the powder acts mainly as a microfiller and secondary aluminosilicate component.

4. The optimized mixture achieved a density of 1605 kg/m³, 28-day compressive strength of 57.0 MPa, flexural strength of 7.50 MPa, drying shrinkage of 0.475 mm/m and thermal conductivity of 0.475 W/(m·K). These results confirm a balanced combination of structural and thermal properties.

5. The calculated specific compressive strength was 35.5 MPa, and the strength-to-conductivity index reached 120 MPa·m·K/W. These indices demonstrate that the proposed design is suitable for hot-dry climatic regions where reduced self-weight, lower heat transfer and stable early hydration are required.

6. For practical production, the most important technological controls are perlite pre-wetting, moisture correction of ceramic waste aggregates, careful mixing sequence and monitoring of particle-size distribution and water absorption for local raw materials.

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