

Effect of Integral Waterproofing on Strength and Durability of Foamed Concrete

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Abstrak

Beton berbusa banyak digunakan dalam konstruksi ringan. Namun, struktur berporinya menyebabkan tingkat penyerapan air yang tinggi serta kerusakan akibat kelembapan, sehingga membatasi masa pakai. Penelitian ini menganalisis pengaruh bahan tambahan kedap air terhadap kepadatan, kekuatan tekan, dan kualitas internal beton berbusa yang dibuat dengan metode busa pra-cetak. Lima jenis campuran diuji: dua campuran referensi dengan superplasticizer polikarboksilat pada dua tingkat busa (2F3-S, 2F5-S) dan tiga campuran dengan bahan tambahan pada dosis 5, 7,5, dan 10 kg/m³ (2F3A5, 2F3A7.5, 2F3A10). Ukuran yang diambil meliputi kepadatan, kekuatan tekan (setelah 1, 3, 7, dan 28 hari), serta kecepatan pulsa ultrasonik (UPV). Hasil menunjukkan bahwa campuran kedap air memiliki kepadatan setelah 28 hari yang lebih tinggi (1911–2020 kg/m³) dan kekuatan (34,4–43,0 MPa) dibandingkan dengan campuran referensi (1665 kg/m³, 21,9 MPa). Kekuatan meningkat sebanding dengan peningkatan jumlah bahan tambahan. Kekuatan pada tahap awal terlihat serupa, yang menandakan bahwa proses hidrasi tidak terhambat. Kepadatan yang lebih tinggi mengindikasikan adanya interaksi antara bahan tambahan dan busa. Pada umur 28 hari, UPV yang diukur lebih tinggi pada campuran kedap air (4,3–4,5 km/s berbanding 2,8–3,3 km/s) dan menunjukkan hubungan yang erat dengan kepadatan ($R^2 = 0,99$), yang mengindikasikan kohesi yang lebih baik dan konektivitas pori yang lebih rendah. Campuran referensi dengan tingkat busa tinggi hanya mencapai kekuatan 8,5 MPa pada kepadatan 1463 kg/m³, yang menunjukkan penurunan kekuatan akibat busa berlebih. Oleh karena itu, bahan kedap air yang terintegrasi dapat meningkatkan kualitas beton berbusa dan efektif digunakan pada elemen yang terpapar kelembapan, seperti panel fasad, atap, dan komponen ringan, serta menawarkan alternatif bagi metode kedap air permukaan.

Kata Kunci: Beton Berbusa, Kedap Air Integral, Kecepatan Pulsa Ultrasonik, Kuat Tekan

Abstract

Foamed concrete is widely used in lightweight construction, but its porous structure leads to high water absorption and moisture damage, thereby limiting durability. This study examines how an integral waterproofing admixture affects density, compressive strength, and internal

quality of foamed concrete produced by the pre-formed foam method. Five mixes were tested: two references with polycarboxylate superplasticizer at two foam levels (2F3-S, 2F5-S) and three with the admixture at 5, 7.5, and 10 kg/m³ (2F3A5, 2F3A7.5, 2F3A10). Density, compressive strength (at 1, 3, 7, and 28 days), and ultrasonic pulse velocity (UPV) were measured. Waterproofed mixes showed higher 28-day density (1911–2020 kg/m³) and strength (34.4–43.0 MPa) than references (1665 kg/m³, 21.9 MPa). Strength rose with admixture dosage. Early-age strengths were similar, so hydration was not hindered. Higher density suggests admixture–foam interaction. At 28 days, UPV was higher in waterproofed mixes (4.3–4.5 km/s vs. 2.8–3.3 km/s) and closely correlated with density ($R^2 = 0.99$), indicating better cohesion and less pore connectivity. The high-foam reference mix had only 8.5 MPa at 1463 kg/m³, showing the strength loss from more foam. Thus, integral waterproofing improves foamed concrete's quality and is effective for moisture-exposed elements like façade panels, roofs, and lightweight components, offering an alternative to surface waterproofing.

Keywords: *Foamed Concrete, Integral Waterproofing, Ultrasonic Pulse Velocity, Compressive Strength*

INTRODUCTION

Foamed concrete (FC) is a lightweight, cement-based material with a cementitious matrix that contains stable air voids produced by physical or chemical foaming. Its low density, excellent thermal insulation, sound absorption, and ease of placement have made FC increasingly relevant for modern construction applications such as wall panels, void filling, roof insulation, and geotechnical backfilling. Despite these advantages, FC suffers from a critical drawback: its highly porous microstructure results in substantial water absorption, permeability, and moisture-driven deterioration, significantly undermining long-term durability and mechanical integrity.

Because the pore system in FC functions as both a structural component and a transport pathway, water ingress accelerates softening, microcrack propagation, shrinkage, ion penetration, and degradation under freeze–thaw or environmental exposure. Porosity and its distribution directly govern mechanical strength, water absorption, and impermeability: higher porosity increases capillary suction and adsorption, weakening the cementitious matrix and reducing service life. Lermen et al. (2019) demonstrated that variations in foam content and binder composition substantially influence FC density, water absorption, and air-void characteristics, ultimately affecting both durability and mechanical strength. More recently, Lv et al. (2024) showed that stabilizing the aqueous foam itself — through hydrophobic modification of the foam phase — refines the pore structure and enables high-performance lightweight FC, underlining how strongly pore architecture controls the balance between density, strength, and moisture resistance.

To mitigate moisture-related degradation, various waterproofing strategies have been explored. Surface-applied hydrophobic treatments such as silane emulsions, organosilicon sealers, and graphene oxide–modified emulsions have been reported to reduce water

permeability, sorptivity, and ice-induced damage. Gao et al. (2021) found that silane emulsions markedly improved the waterproofing and anti-icing performance of FC, and Shi et al. (2022) showed that graphene oxide–modified silane emulsions produced highly water-repellent FC surfaces with refined pore structures and delayed moisture ingress under environmental exposure. However, external coatings suffer from inherent long-term limitations, including aging, abrasion, cracking, and delamination. These weaknesses reduce their effectiveness over time, particularly under UV radiation, freeze–thaw cycling, or mechanical wear — issues consistently highlighted in superhydrophobic FC research (Mao et al., 2025).

Recent research trends have therefore shifted toward integral or bulk hydrophobic modification, wherein hydrophobic agents are incorporated directly into the FC mixture during preparation. Instead of forming a protective film only on the exterior, integral waterproofing reduces surface energy inside the pore system, obstructs capillary pathways, and modifies the pore structure at the micro-scale. Several admixture-based strategies have been examined. Epoxy resin has been shown to create internal micro-networks that reduce pore size, disrupt continuous capillaries, and enhance impermeability while lowering drying shrinkage (Gong & Li, 2020). Water-repellent admixtures incorporated during mixing have likewise been reported to reduce the water absorption and sorptivity of FC at relatively low dosages (Lee et al., 2018). Nano-SiO₂ aerogels, combined with organosilicon waterproofing agents, improve both thermal and waterproofing performance (Cheng et al., 2022), and supplementary cementitious materials and industrial by-products further contribute to the densification of the FC matrix, enhancing both mechanical strength and moisture resistance (Wu et al., 2025).

Alongside these matrix-level approaches, advances in superhydrophobic technologies have introduced new pathways for reducing water ingress in FC. Superhydrophobic foamed concrete aims to achieve contact angles greater than 150°, thereby drastically reducing water uptake and altering water–solid interactions at the material surface (Sun et al., 2023). Mao et al. (2025) demonstrated that PDMS-modified foamed concrete prepared via physical foaming reduced volumetric water absorption by 72.4% and capillary absorption by 92.6%, while maintaining exceptional resistance to ultraviolet radiation, mechanical wear, chloride ingress, and extreme temperatures. Such bulk modification is particularly promising because the hydrophobic groups remain embedded throughout the matrix rather than residing only on the exterior layer, thereby preserving long-term performance despite abrasion or environmental degradation.

Despite these advancements, existing research still leaves significant gaps. Much prior work has focused on surface-modified superhydrophobic FCs or on hydrophobic systems prepared via chemical foaming, which differ in stability and porosity from FCs prepared using pre-formed foam. Other studies have investigated specialized composite approaches — such as aerogel impregnation or graphene oxide-based treatments — but these often emphasize advanced surface functionalities rather than fundamental improvements in structural performance. Moreover, studies seldom evaluate the combined effects of density, compressive strength development, ultrasonic pulse velocity (UPV), and admixture dosage in integral waterproofing systems, and serviceability-oriented reviews

continue to identify moisture-related degradation as the principal obstacle to wider FC adoption (Zhou & Leung Su, 2024). The absence of a matrix-level evaluation of commercially available integral waterproofing admixtures in FC prepared through the pre-formed foam method highlights a clear need for further investigation.

In response to these gaps, the present study examines the effect of a commercial integral waterproofing admixture, applied at three dosages, on the density, compressive strength development, and UPV of foamed concrete produced using a pre-formed physical foaming method, benchmarked against superplasticized reference mixtures at two foam dosages. By evaluating internal waterproofing rather than surface treatments, this work aims to contribute to a more stable, long-term solution to moisture-related degradation in lightweight foamed concrete and to the development of durable, functional FC suitable for a wide range of construction applications.

MATERIALS AND METHODS

The experimental program was designed to determine the effect of an integral waterproofing admixture on the density, compressive strength development, and internal quality of foamed concrete. All specimens were produced using the pre-formed foam method to ensure stable cell formation and consistent pore distribution. The program comprised material preparation, controlled mixing, specimen casting, curing, and laboratory testing of density, compressive strength, and ultrasonic pulse velocity (UPV).

MATERIALS

Ordinary Portland cement, natural river sand, potable water, a commercial pre-formed foaming agent, a polycarboxylate-based superplasticizer, and a commercial integral waterproofing admixture (referred to in this paper as Product M) were used as the primary materials. All materials were stored under stable laboratory conditions to minimize variability during testing.

MIX PROPORTIONS AND SAMPLE DESIGNATION

Five mixtures were produced, comprising two superplasticized reference mixtures at different foam dosages and three mixtures incorporating the integral waterproofing admixture at increasing dosage. For each cubic meter of foamed concrete, the base proportions consisted of 500 kg of cement, 731.09 kg of sand, and 142.5 kg of water, corresponding to a water–cement ratio of 0.285, combined with pre-formed foam. In the reference mixtures, the polycarboxylate superplasticizer was dosed at 7.5 kg/m³ to ensure adequate workability at this low water content; in the waterproofed mixtures, Product M was incorporated at 5, 7.5, or 10 kg/m³ in place of the superplasticizer. The entrained-air volume generated by the foam was approximately 35.6% of the total mixture volume at the F3 foam dosage. At the same time, the F5 designation corresponds to a higher foam dosage targeting a lower density class. Table 1 summarizes the mix proportions, and Table 2 defines the sample designations used throughout this paper: the prefix identifies the foam dosage (2F3 or 2F5), while the suffix identifies the admixture (S for superplasticizer; A5, A7.5, and A10 for Product M at 5, 7.5, and 10 kg/m³, respectively).

Table 1. Mix proportions of the foamed concrete mixtures

Mixture		Cement (kg/m ³)	Sand (kg/m ³)	Water (kg/m ³)	SP (kg/m ³)	Product M (kg/m ³)
2F3-S	500	731.09	142.5	7.5	–	
2F5-S	500	731.09	142.5	7.5	–	
2F3A5	500	731.09	142.5	–	5.0	
2F3A7.5	500	731.09	142.5	–	7.5	
2F3A10	500	731.09	142.5	–	10.0	

Table 2. Sample designations

Mixture	Description	Admixture
2F3-S	Reference, foam dosage F3	Superplasticizer, 7.5 kg/m ³
2F5-S	Reference, foam dosage F5	Superplasticizer, 7.5 kg/m ³
2F3A5	Integral waterproofing, foam dosage F3	Product M, 5 kg/m ³
2F3A7.5	Integral waterproofing, foam dosage F3	Product M, 7.5 kg/m ³
2F3A10	Integral waterproofing, foam dosage F3	Product M, 10 kg/m ³

FOAM GENERATION, MIXING, CASTING AND CURING

The foam was generated separately using a high-speed mechanical foaming machine. The foaming agent was first diluted with water according to the manufacturer's recommendations and then aerated to produce a uniform, stable foam. Its density was checked periodically to maintain consistency across batches; preparing the foam independently from the cementitious paste minimized bubble collapse and ensured a uniform pore structure.

Mixing followed a standardized sequence. The cement and sand were first blended dry in a mechanical mixer until a uniform powder was obtained. The liquid admixture (superplasticizer or Product M) was pre-dissolved in the mixing water to ensure uniform dispersion, and this solution was gradually added to the dry blend until the paste was fully homogenized. Once the cement–sand paste reached a consistent, workable state, the pre-formed foam was gently folded into the paste rather than mixed at high speed to avoid damaging the foam structure. Mixing continued until the foam was evenly distributed and the mixture achieved a cohesive, stable consistency.

The fresh mixtures were cast into cylindrical molds with a diameter of 100 mm and a height of 200 mm. After casting, the specimens were covered to prevent moisture loss and left undisturbed for 24 hours, then carefully demolded and cured in water under controlled laboratory conditions until the designated testing ages of 1, 3, 7, and 28 days. Two to three replicate specimens were tested for each mixture and age.

TEST METHODS

The density of each specimen was determined from its mass and dimensions at the time of testing. Compressive strength was measured at 1, 3, 7, and 28 days using a servo-controlled universal testing machine at a constant loading rate, and the reported strengths are the mean values of replicate specimens at each age. UPV testing was conducted as a non-destructive method to assess internal quality: ultrasonic transducers were placed on opposite faces of the specimens in direct transmission, and the pulse velocity was computed from the measured travel time and path length. Higher pulse velocities were interpreted as indicators of improved internal cohesion and reduced pore connectivity.

RESULTS AND DISCUSSION

This section presents the experimental results for density, compressive strength development, and ultrasonic pulse velocity and interprets them in light of previous research on hydrophobically modified foamed concrete. Emphasis is given to the dual performance requirement of lightweight concretes: maintaining sufficient compressive strength for structural adequacy while improving the internal quality that governs resistance to moisture ingress.

DENSITY AND COMPRESSIVE STRENGTH

Table 3. Mean compressive strength development, 28-day density, and 28-day UPV of all mixtures

Mixture	1 day (MPa)	3 days (MPa)	7 days (MPa)	28 days (MPa)	28- days density (kg/m ³)	28- days UPV (km/s)
2F3-S	-	13.36	16.97	21.85	1665	3.28
2F5-S	-	-	-	8.48	1463	2.83
2F3A5	17.18	24.82	28.95	34.36	1911	4.31
2F3A7.5	21.32	25.77	28.00	39.45	2003	4.40
2F3A10	20.05	26.41	30.23	42.95	2020	4.50

Table 3 summarizes the strength development, 28-day density, and 28-day UPV of all mixtures. The reference mixture 2F3-S reached a 28-day compressive strength of 21.85 MPa at a density of 1665 kg/m³, satisfying the requirements for structural lightweight concrete, for which densities up to approximately 1750 kg/m³ are commonly cited (Lee et al., 2018). The higher-foam reference 2F5-S, in contrast, reached only 8.48 MPa at 1463 kg/m³, confirming the well-established strength penalty associated with increased foam content (Lermen et al., 2019) and thereby restricting this mixture to non-structural applications such as insulation and void filling.

The waterproofed mixtures exhibited a distinctly different behavior. All three developed substantially higher densities (1911–2020 kg/m³ at 28 days) and higher strengths at every age than the reference at the same nominal foam dosage, with 28-day strengths of

34.36, 39.45, and 42.95 MPa for Product M dosages of 5, 7.5, and 10 kg/m³, respectively. Strength increased monotonically with admixture dosage. Two mechanisms plausibly contribute to this behavior. First, the hydrophobic agent lines the pore walls and disrupts capillary continuity without interfering with hydration, thereby allowing the formation of calcium–silicate–hydrate (C–S–H) gel — the primary binding product responsible for strength in cementitious materials — to proceed unimpeded (Ying et al., 2025). The vigorous early-age strengths (17–21 MPa at 1 day) support the conclusion that hydration kinetics were not retarded. Second, the higher hardened densities indicate a partial destabilization or reduced expansion of the pre-formed foam in the presence of the admixture, producing a denser matrix; the strength gain of the waterproofed mixtures is therefore attributable to the combined effect of pore-wall modification and densification rather than to pore-structure refinement alone.

This densification represents a trade-off that must be recognized. While the waterproofed mixtures comfortably exceeded structural strength requirements, their 28-day densities rose above the range conventionally associated with structural lightweight concrete. Where the lightweight density class is a governing design criterion, the foam dosage or admixture dosage would need to be adjusted to recover the target density while retaining the improvement in internal quality; conversely, where moderate density is acceptable, the waterproofed mixtures offer a substantial strength reserve.

Previous studies support the finding that hydrophobic admixtures need not compromise strength. Wu et al. (2025) reported that the incorporation of industrial by-products in lightweight foamed concrete improved impermeability without reducing mechanical strength; Cheng et al. (2022) observed that organosilicon-based waterproofing agents improved thermal and waterproofing properties while retaining compressive strength; and Sun et al. (2023) and Mao et al. (2025) highlighted that superhydrophobic modifications enhanced durability without compromising strength development. An evaluation of integral and surface hydrophobic treatments likewise demonstrated that improvements in permeation resistance were achieved without adverse effects on compressive strength (Ying et al., 2025). Collectively, these studies indicate that hydrophobic admixtures act by refining the pore structure and reducing water pathways while maintaining matrix integrity.

UPV ANALYSIS

Ultrasonic pulse velocity was employed as a non-destructive indicator of internal microstructural quality: higher pulse velocities are generally associated with denser, more homogeneous microstructures and lower interconnected porosity. As shown in Table 3, the waterproofed mixtures consistently exhibited higher UPV values at 28 days (4.31–4.50 km/s) than the reference mixtures (3.28 km/s for 2F3-S and 2.83 km/s for 2F5-S), and UPV increased with admixture dosage in the same order as density and strength. This improvement indicates that incorporating the integral waterproofing admixture enhanced internal cohesion and reduced interconnected voids, consistent with the densification identified in the preceding subsection. The hydrophobic admixture is understood to contribute to a refined pore structure by lining the pore walls and reducing the capillary channels available for water ingress (Ying et al., 2025).

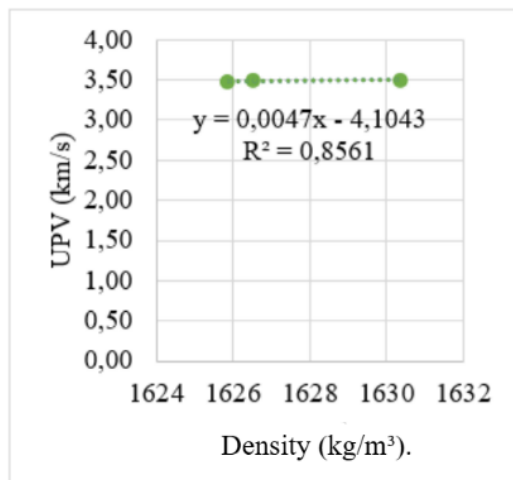


Fig. 1. Regression between density and UPV for mixtures 2F5 and 2F3 at 3 days of curing

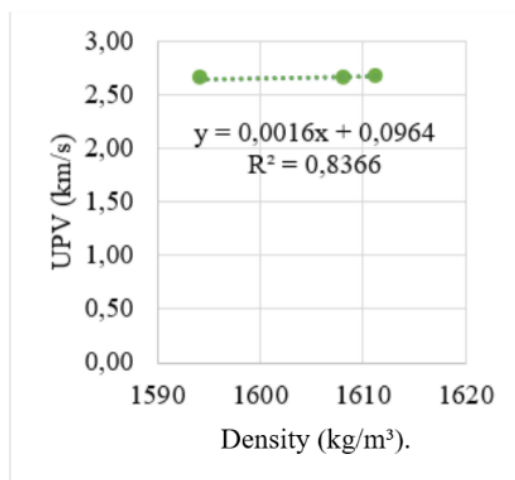


Fig. 2. Regression between density and UPV for mixtures 2F5 and 2F3 at 7 days of curing (UPV = 0.0016ρ + 0.0964; R² = 0.837).

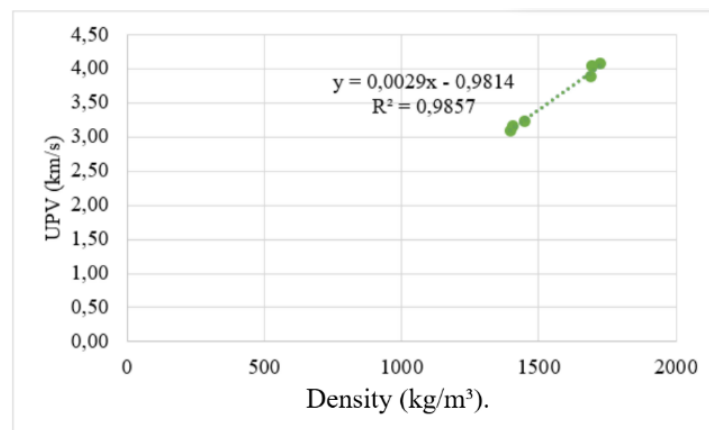


Fig. 3. Regression between density and UPV for mixtures 2F5 and 2F3 at 28 days of curing ($UPV = 0.0029\rho - 0.9814$; $R^2 = 0.986$).

Figures 1–3 show the regression between density and UPV for the reference series at 3, 7, and 28 days. The correlation strengthens markedly with age, reaching $R^2 = 0.986$ at 28 days, confirming that density is the dominant variable governing pulse velocity in these mixtures once hydration has matured, and that UPV can serve as a reliable non-destructive proxy for the internal quality of foamed concrete. This finding reinforces the practical value of UPV for the quality control of lightweight elements, where coring or destructive testing is often impractical.

Previous research supports these observations. Cheng et al. (2022) reported that nano-SiO₂ aerogels and organosilicon waterproofing agents reduced pore connectivity, enhancing both waterproofing and thermal performance; Gong and Li (2020) highlighted that epoxy-resin modification improved impermeability and reduced microcracking, resulting in better ultrasonic propagation within the material; Shi et al. (2022) and Gao et al. (2021) demonstrated that silane- and graphene oxide-based modifications refine pore structures while maintaining mechanical strength. Sun et al. (2023) confirmed that superhydrophobic modifications created a hierarchical roughness that improved both strength and durability by limiting pore interconnectivity.

GENERAL DISCUSSION

The combined results of density, compressive strength, and UPV provide a coherent picture of the effect of the integral waterproofing admixture on foamed concrete produced by the pre-formed foam method. At the same nominal foam dosage, the admixture produced denser, stronger, and internally more homogeneous concrete than the superplasticized reference, with strength and UPV increasing monotonically with dosage. The admixture clearly did not retard hydration; on the contrary, strength development from 1 to 28 days was vigorous at all three dosages, and the hydration kinetics appear essentially unaffected, with

the admixture functioning primarily by modifying the pore system rather than the binding phase.

At the same time, the results reveal an interaction between the admixture and the pre-formed foam that manifests as densification. Establishing whether this arises from bubble destabilization during mixing, from changes in paste rheology in the absence of the superplasticizer, or from a combination of both requires fresh-density and air-content measurements, which are recommended for subsequent studies. If controlled, adjustments to dosage or foam content would allow recovery to the target density class while retaining the improvement in internal quality demonstrated here.

From a practical viewpoint, integral admixtures retain a decisive advantage over surface-applied methods: coatings, while initially effective, are prone to mechanical damage, delamination, and weathering, whereas integral admixtures provide uniform protection throughout the matrix, ensuring long-term performance even when the concrete surface is exposed to abrasion or environmental stress (Gong & Li, 2020; Mao et al., 2025). The high internal quality of the waterproofed mixtures — reflected in their UPV values — suggests suitability for moisture-exposed elements such as façade panels, roofing elements, and lightweight blocks, where both serviceability and long-term durability are demanded.

CONCLUSION

This study investigated the effect of a commercial integral waterproofing admixture, applied at dosages of 5, 7.5, and 10 kg/m³, on foamed concrete produced by the pre-formed foam method, benchmarked against superplasticized reference mixtures at two foam dosages. The following conclusions can be drawn.

First, the admixture did not impede cement hydration or strength development: the waterproofed mixtures reached 28-day compressive strengths of 34.4–43.0 MPa, increasing monotonically with dosage, compared with 21.9 MPa for the reference at the same foam dosage. Second, the waterproofed mixtures exhibited consistently higher ultrasonic pulse velocities at 28 days (4.3–4.5 km/s versus 2.8–3.3 km/s for the references). UPV correlated strongly with density ($R^2 = 0.986$ at 28 days), indicating enhanced internal cohesion and reduced pore connectivity, and confirming UPV as a reliable non-destructive quality indicator for foamed concrete. Third, the incorporation of the admixture was accompanied by a marked increase in hardened density (1911–2020 kg/m³ versus 1665 kg/m³ for the reference), indicating an interaction between the admixture and the pre-formed foam that must be controlled if the material is to remain within the structural lightweight density class. Fourth, the higher-foam reference mixture reached only 8.5 MPa at 1463 kg/m³, confirming a severe strength penalty associated with increased foam content and thereby restricting such mixtures to non-structural use.

In general, integral waterproofing embeds hydrophobicity within the matrix rather than on the surface, providing more reliable long-term protection than coatings, which are prone to damage and deterioration. Future work should quantify the foam–admixture interaction through fresh-density and air-content measurements, complete the hygric characterization of these mixtures — water absorption, sorptivity, and softening coefficient under wetting–drying cycles — and explore synergies with supplementary cementitious materials, industrial by-

products, or hybrid hydrophobic agents to recover lower density classes while retaining the improvements in strength and internal quality demonstrated here.

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