Preparation, Performance, and Environmental Deterioration of Cement-Based Self-Insulating Wall Materials

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Abstract: This study focuses on cement-based self-insulating wall materials, conducting experimental research on pore structure control, optimization of fundamental properties, and performance degradation under high humidity and thermal conditions. Using 42.5-grade Portland cement as the primary binder, modified sodium rosinate as the foaming agent, and waste engine oil as the foam stabilizer, cement-based self-insulating wall materials with varying water-to-cement ratios and pore sizes were prepared via physical foaming. The true density, apparent density, water absorption rate, closed-pore ratio, compressive strength, and microstructure were tested. Subsequently, a coupled high-temperature-high-humidity environment (40 °C, 80% RH) was applied to analyze the effects of temperature and humidity on the material's thermal conductivity and mechanical properties. Results indicate that both water-to-cement ratio and pore size significantly influence the pore structure and macroscopic performance. Excessively high water-to-cement ratios increase interconnected pores and visible voids, leading to higher water absorption, lower closed-pore content, and reduced material strength. Conversely, excessively large pore sizes tend to cause thinning of pore walls, pore interconnection, and structural delamination, which hinder the simultaneous improvement of insulation and mechanical performance. When the water-to-cement ratio is 0.50 and pore size ranges from 1.0 to 2.5 mm, the material exhibits optimal overall performance: a closed-pore ratio of 34.59%, water absorption of 11.30%, compressive strength of 6.15 MPa, a thermal conductivity of 0.087 $W \cdot m^{-1} \cdot K^{-1}$ in dry condition, and 0.099 $W \cdot m^{-1} \cdot K^{-1}$ after exposure to high humidity and heat—representing a degradation rate of only 13.79%. In contrast, samples with high water-to-cement ratios and large pores show significantly increased thermal conductivity under humid-heat conditions, indicating greater environmental sensitivity. The study demonstrates that an appropriate water-to-cement ratio combined with moderate pore size promotes a higher closed-pore ratio and more stable pore structure, enabling coordinated optimization of lightweight, thermal insulation, mechanical strength, and resistance to moisture-heat degradation in cement-based self-insulating wall materials.

Key words: Cement-Based Self-Insulating Wall Materials; Physical Foaming; Water–Cement Ratio; Pore Size; Coupled High Temperature and Humidity Environment

1. Introduction

Building energy efficiency is a key link in achieving the "dual carbon" goals. Within this context, cement-based self-insulating wall materials have increasingly become a focal technology for upgrading envelope systems because they integrate load-bearing capacity with thermal-insulation functionality [1]. In this material system, the cementitious matrix is combined with an intentionally regulated pore network generated through foaming. Owing to the intrinsically low thermal conductivity of entrapped air, the material can achieve thermal insulation while largely retaining the characteristic merits of cement-based products, including comparatively high strength, satisfactory durability, and construction convenience. Consequently, such materials have been adopted extensively in both industrial and civil building applications [2].

Despite this progress, several unresolved constraints remain. The first concerns the persistent difficulty of reconciling thermal-insulation efficiency with mechanical strength. The second involves moisture-sensitive deterioration under hot-humid service conditions. The third is the inadequacy of thermal inertia in practical applications. Among the governing variables, the w/c ratio directly regulates slurry rheology as well as compactness of the hardened matrix, whereas pore size and closed porosity exert decisive influence on both thermal-insulation behavior and mechanical performance [3,4]; in southern hot-humid regions in particular, moisture ingress can significantly elevate thermal conductivity and simultaneously impair interfacial bonding, thereby accelerating long-term performance deterioration [5-7].

Accordingly, the present study is organized into two interrelated components. The first component addresses the preparation of cement-based self-insulating wall materials with different w/c ratios and pore sizes, with the aim of elucidating the evolution of their physical properties, mechanical properties, and microstructural characteristics. The second component imposes a simulated coupled high temperature and humidity environment so as to quantitatively characterize environmentally induced deterioration in mechanical performance and thermal performance.

2. Materials and Equipment

2.1 Materials

Cementitious material: 42.5-grade Portland cement, compliant with GB 175–2023 General Portland Cement [8], true density 3.1 g/cm³, 28-day compressive strength 48.5 MPa.

Foaming agent: modified sodium abietate (industrial grade), solid content 30%, foaming ratio 25 times.

Foam stabilizer: waste engine oil (industrial grade) to enhance foam stability and reduce foam breakage and pore collapse.

Mixing water: ordinary tap water.

2.2 Equipment

Mixing equipment: JJ-5 type planetary cement paste mixer.

Foaming equipment: FP-X100 type physical foamer, capable of producing foams with different pore sizes.

Curing equipment: Standard curing chamber (20 ± 2 °C, ≥95% RH). Constant temperature and humidity curing chamber.

Moulds: Cube moulds: 100 mm × 100 mm × 100 mm. Plate moulds: 300 mm × 300 mm × 30 mm.

Testing equipment: Electronic analytical balance (accuracy 0.001 g). True density instrument. Pressure testing machine. Thermal conductivity meter. Scanning electron microscope (SEM).

Other equipment: Vacuum drying oven. Vernier calipers, etc.

3. Experimental Scheme and Methods

3.1 Preparation and Performance Testing of Cement-Based Self-Insulating Wall Material

3.1.1 Experimental principle

For cement-based self-insulating wall materials, thermal-insulation capacity is governed predominantly by structural descriptors, especially porosity, pore size, and closed porosity. By contrast, the w/c ratio serves as a primary control parameter for slurry fluidity, setting-hardening behavior, and strength development. Through determination of true density, apparent density, and water absorption, total porosity, open porosity, and closed porosity can be derived quantitatively. When these indices are interpreted together with compressive strength and SEM-based microstructural characterization, the effects of w/c ratio and pore size on physical properties, mechanical properties, and internal morphology can be systematically delineated.

3.1.2 Preparation process

Foam solution preparation: Using a physical foaming method, modified sodium abietate, waste engine oil, and tap water were mixed at specified ratios. Foam solutions with pore sizes of 0.2–1.0 mm, 1.0–2.5 mm and 2.5–10.0 mm were then prepared by a foaming machine for later use.

Cement slurry preparation: For w/c ratios of 0.45, 0.50, and 0.55, cement and tap water were weighed and mixed in a planetary mixer for 3 minutes to obtain uniform slurry.

Mixing and Pouring: The foam solution and cement paste were mixed at a volume ratio of 2：1, stirred for an additional 1 minute, poured into molds, lightly vibrated 15 times, and the surface was scraped flat.

Standard curing: Specimens were placed in a standard curing box at 20 ± 2 °C and ≥95% RH for 28 days.

3.1.3 Property testing methods

True density was measured using a true density apparatus in accordance with JG/T 266–2011 Foamed Concrete. For each test group, at least three specimens were tested, and the average value was calculated.
Apparent density test: After curing for 28 days, the specimens were removed and any surface moisture was wiped off. The mass was measured using an electronic balance, and the dimensions were measured with a vernier caliper to calculate the apparent density. For each test group, at least three specimens were tested, and the average value was calculated.
Water absorption test: Specimens were placed in a vacuum drying oven and dried at 105 °C until a constant mass was achieved. The dry mass was weighed and recorded as m_1. The specimens were then completely immersed in tap water and soaked for 24 h. After removal, surface water was wiped off, and the saturated mass was weighed and recorded as m_2. Water absorption is calculated by the formula: $W_a=(m_2-m_1)/m_1\times100\%$.
Closed porosity calculation: Based on true density (ρ_{th}), apparent density (ρ_{app}), and water absorption (W_a), the closed porosity (P_c) is calculated using the following relations: total porosity: $P=(1-\rho_{app}/\rho_{th})\times100\%$, open porosity: $P_a=W_a\times\rho_{app}$, closed porosity: $P_c=P-P_a$.
Compressive Strength Test: Using a compression testing machine, compressive strength tests were conducted on 100 mm × 100 mm × 100 mm cubic specimens in accordance with GB/T 50081–2019 Standard for Test Methods of Physical and Mechanical Properties of Concrete. The loading rate was set at 0.2 MPa/s. At least three specimens were tested per group, and the arithmetic average value was adopted as the final result.
Microstructural observation: After the compressive strength test, representative fragments were cut from the specimens. The samples were ground, dried, and sputter-coated with gold. The internal pore structure, morphology of cement hydration products, and interfacial bonding state were then examined via SEM. The effects of different variables on the microstructure were analyzed accordingly.

3.2 Deterioration Effect of High Temperature –Humidity Coupling Environment on Self-Insulating Wall Panels

3.2.1 Experimental principle
Under a coupled high temperature and humidity environment, moisture penetration is accelerated and pore-structure deterioration is intensified. These processes induce softening of cement hydration products and weaken interfacial bonding. As a consequence, thermal conductivity increases, whereas compressive strength declines. In the present work, a southern hot-humid climatic condition was simulated at 40 °C and 80% RH. A dry environment, maintained at 20 ± 2 °C and 50 ± 5% RH, served as the control condition. Material deterioration trends were assessed through calculation of the performance deterioration rate.
3.2.2 Experimental plan
Specimen selection: Specimens with water-cement ratios of 0.45, 0.50, and 0.55 and pore-size ranges of 0.2–1.0 mm, 1.0–2.5 mm, and 2.5–10.0 mm were selected. Each group contained three specimens.
Pre-treatment: All specimens were cured under standard conditions for 28 days.
Environmental simulation: The experimental group was conditioned at 40 °C, 80% RH for 28 days, while the control group was conditioned under the dry environment.
Performance testing: Compressive strength and thermal conductivity were measured, and the deterioration rate was calculated.

4. Experimental Results and Analysis

4.1 Preparation and Performance Analysis of Cement-Based Self-Insulating Wall Materials

4.1.1 Physical performance analysis
The test results of true density, apparent density, water absorption and closed porosity of cement-based self-insulating specimens with different w/c ratios and pore sizes are presented in Table 1 and Table 2.

Table 1. Effect of w/c Ratio on Physical Properties

W/C	Pore size(mm)	True density(g/cm³)	Apparent density(g/cm³)	Total porosity(%)	Water absorption(%)	Open porosity(%)	Closed porosity(%)
0.45	1.0-2.5	2.86	1.53	46.50	10.30	15.76	30.74
0.50	1.0-2.5	2.85	1.41	50.53	11.30	15.93	34.59
0.55	1.0-2.5	2.83	1.34	52.65	21.10	28.27	24.38

Table 2. Effect of Pore Size on Physical Properties

W/C	Pore size(mm)	True density(g/cm³)	Apparent density(g/cm³)	Total porosity(%)	Water absorption(%)	Open porosity(%)	Closed porosity(%)
0.50	0.2-1.0	2.85	1.51	47.02	11.90	17.97	29.05
0.50	1.0-2.5	2.85	1.41	50.53	11.30	15.93	34.59
0.50	2.5-10.0	2.85	1.44	49.47	24.10	34.70	14.77

As shown in Table 1, with the pore size fixed at 1.0–2.5 mm, the true density of the specimens remained relatively stable as the w/c ratio increased from 0.45 to 0.55. By contrast, the apparent density fell from 1.53 g/cm^3 to 1.34 g/cm^3, accompanied by a marked rise in total porosity from 46.50% to 52.65%. Such a shift is mainly associated with the greater amount of free water introduced into the cement paste at a higher w/c ratio; during hardening, the evaporation of this excess water leaves additional voids, thereby loosening the overall structure. In parallel, water absorption increased significantly from 10.30% to 21.10%, open porosity rose from 15.76% to 28.27%, and closed porosity decreased from 30.74% to 24.38%. These changes indicate that an excessively high w/c ratio disrupts pore structure integrity, converting a substantial number of closed pores into interconnected pores and facilitating water penetration into the material interior, which in turn increases water absorption, reduces air retention capacity, and is unfavorable to both thermal insulation and durability.

As shown in Table 2, when the w/c ratio was held constant at 0.50, the apparent density of the specimens remained relatively consistent, despite minor fluctuations, as the pore size increased from 0.2–1.0 mm to 2.5–10.0 mm. Over the same range, however, water absorption rose sharply from 11.90% to 24.10%, open porosity increased from 17.97% to 34.70%, and the closed porosity declined significantly from 29.05% to 14.77%. Smaller pore sizes, under the mixing and molding conditions used here, are more conducive to forming uniform and stable spherical closed pores that are less likely to interconnect. Larger pores, in contrast, are more prone to coalescence and rupture during these operations, promoting the formation of interconnected pores and micro-cracks. As a result, water infiltration paths expand substantially, open porosity increases, and the closed porosity is markedly reduced. Accordingly, smaller and medium pore sizes are more favorable for obtaining a superior pore structure characterized by a high closed porosity and low water absorption.

4.1.2 Mechanical properties analysis

The 28-day compressive strength test results of cement-based self-insulating specimens with different w/c ratios and pore sizes are shown in Table 3 and Table 4.

Table 3. Effect of w/c Ratio on Mechanical Properties

W/C	Pore size(mm)	Compressive strength(MPa)
0.45	1.0-2.5	7.52
0.50	1.0-2.5	6.15
0.55	1.0-2.5	5.56

Table 4. Effect of Pore Size on Mechanical Properties

W/C	Pore size(mm)	Compressive strength(MPa)
0.50	0.2-1.0	6.29
0.50	1.0-2.5	6.15
0.50	2.5-10.0	5.41

As shown in Table 3, at a fixed pore size, the compressive strength of the specimens declined steadily with increasing w/c ratio: 7.52 MPa at 0.45, 6.15 MPa at 0.50, and only 5.56 MPa at 0.55. This reduction is mainly associated with three factors. With a higher w/c ratio, the cement hydration products become more loosely arranged, lowering the compactness of the matrix. Meanwhile, the increase in internal capillary pores and interconnected pores makes stress concentration under load more likely, and the reduced paste viscosity weakens the interfacial bonding force between the foam and the cement matrix, leaving a weak area under stress. Accordingly, maintaining a relatively low w/c ratio is essential for ensuring the mechanical properties of self-insulating materials.

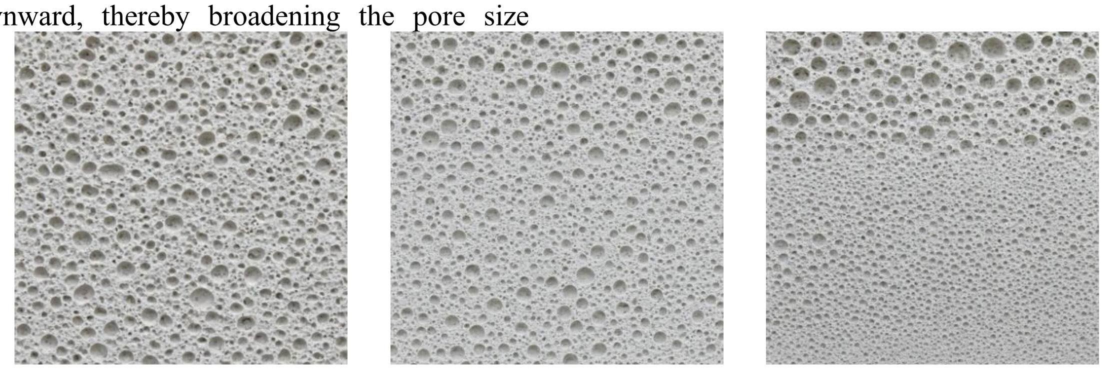
As shown in Table 4, under the same w/c ratio, increasing pore size caused a slight decrease in compressive strength: 6.29 MPa at 0.2–1.0 mm, 6.15 MPa at 1.0–2.5 mm, and 5.41 MPa at 2.5–10.0 mm. Specimens with larger pores exhibited lower strength mainly because the pore walls of large-diameter pores were thinner and more prone to bending and fracture under stress. At the same time, large pores are more likely to develop irregular shapes, further intensifying the stress concentration effect. By comparison, small-diameter pores are more uniformly distributed, with thicker pore walls and better structural continuity, allowing mechanical properties to be retained more effectively while pores are introduced to reduce thermal conductivity.

4.1.3 Micromorphology analysis

The micromorphology of specimens prepared with various w/c ratios and pore sizes was characterized via SEM, with the results shown below.

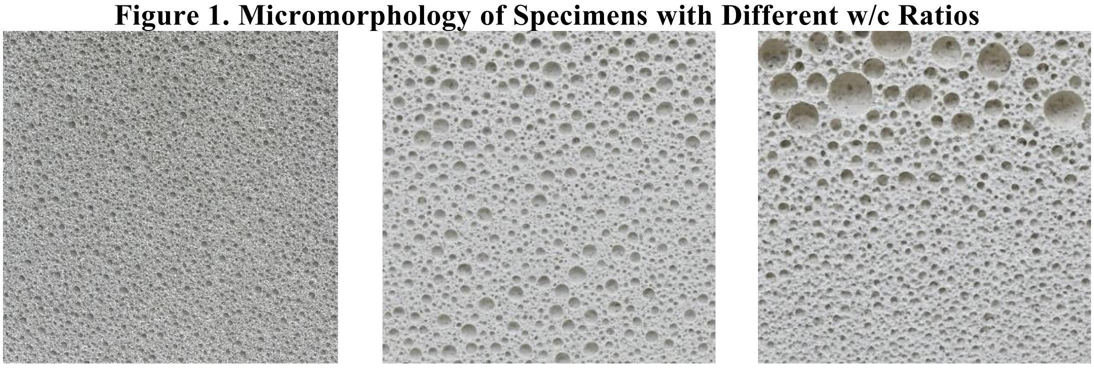
As shown in Figure 1, when the pore size range was fixed at 1.00–2.5 mm, specimens with w/c ratios of 0.45 and 0.50 presented a homogeneous pore distribution, with pores mainly circular or elliptical in shape, pore walls that remained continuous and relatively thick, and a high proportion of closed pores. Cement hydration products were evenly dispersed throughout the matrix, with no detectable microcracks or pore wall damage. Such a compact and uniform pore architecture accounts for the superior compressive strength and low water absorption. At a w/c ratio of 0.55, however, the microstructure showed obvious deterioration: pore stratification occurred, with large pores migrating upward and small pores settling downward, thereby broadening the pore size distribution. In addition, pore walls became thinner, local pore interconnection emerged, and microcracks appeared. These defects reduce closed porosity and increase water absorption, ultimately compromising the mechanical properties of the material.

As shown in Figure 2, at a constant w/c ratio of 0.50, specimens with pore sizes of 0.2–1.0 mm and 1.0–2.5 mm exhibited a homogeneous pore architecture, regular pore morphology, excellent pore wall continuity, and no detectable pore coalescence or stratification. This microstructure favors high closed porosity, thus maintaining low water absorption and sound mechanical properties. By contrast, in the 2.5–10.0 mm pore size group, pronounced pore stratification was observed, with large pores migrating to the upper part of the specimen while small pores remained in the lower zone. Local thinning of the large pore walls led to rupture and interconnection, forming continuous pore pathways. These structural defects weaken the overall integrity of the material and shorten water transport paths, which in turn increases water absorption and reduces compressive strength.



(a) W/C = 0.45 (b) W/C = 0.50 (c) W/C = 0.55

Figure 1. Micromorphology of Specimens with Different w/c Ratios



(a) 0.2–1.0mm (b) 1–2.5mm (c)2.5–10.0mm

Figure 2. Micromorphology of Specimens with Different Pore Sizes

4.2 Deterioration of Self-Insulating Walls under a Coupled High Temperature and Humidity Environment

The compressive strength, thermal conductivity and deterioration rate of specimens with various

w/c ratios and pore sizes, tested under both dry and coupled high temperature and humidity conditions, are presented in Table 5 and Table 6.
As shown in Table 5, thermal conductivity increased markedly for all specimens after exposure to the high temperature-humidity condition (40 ℃, 80% RH). At w/c = 0.45, it rose from 0.119 to 0.153 W/(m·K), corresponding to a 28.57% deterioration rate; at w/c = 0.50, it increased from 0.087 to 0.099 W/(m·K), with a 13.79% deterioration rate; at w/c = 0.55, it jumped dramatically from 0.084 to 0.221 W/(m·K), reaching a deterioration rate of 163.10%. Deterioration becomes more severe as the w/c ratio increases, because specimens with higher w/c ratios contain more interconnected internal pores that facilitate moisture ingress and pore saturation [9,10.

Table 5. Effect of w/c Ratio on Thermal Performance

W/C	Pore size (mm)	Dry-state thermal conductivity ($W\cdot m^{-1}\cdot K^{-1}$)	Hygrothermal-state thermal conductivity($W\cdot m^{-1}\cdot K^{-1}$)	Deterioration rate (%)
0.45	1.0-2.5	0.119	0.153	28.57
0.50	1.0-2.5	0.087	0.099	13.79
0.55	1.0-2.5	0.084	0.221	163.10

Table 6. Effect of Pore Size on Thermal Performance

W/C	Pore size(mm)	Dry-state thermal conductivity ($W\cdot m^{-1}\cdot K^{-1}$)	Hygrothermal-state thermal conductivity($W\cdot m^{-1}\cdot K^{-1}$)	Deterioration rate (%)
0.50	0.2-1.0	0.091	0.129	41.76
0.50	1.0-2.5	0.087	0.099	13.79
0.50	2.5-10.0	0.094	0.231	145.74

As shown in Table 6, the deterioration degree depended strongly on pore size: the deterioration rate was 41.76% for 0.2–1.0 mm pores, 13.79% for 1.0–2.5 mm pores, and up to 145.74% for 2.5–10.0 mm pores. Large-pore specimens showed the most pronounced deterioration, since large pores readily develop continuous pore networks that enable rapid moisture uptake and high saturation water content. Considering that the thermal conductivity of water (~0.6 W/(m·K)) is vastly higher than that of air, pore saturation sharply diminishes thermal insulation performance.

5. Conclusions

Water-cement ratio and pore size strongly influence the performance of cement-based self-insulating materials. The optimal formulation is identified at w/c = 0.50 and a pore size range of 1.0–2.5 mm, which features high closed porosity, low water absorption, favorable compressive strength and compact microstructure.
Exposure to the coupled high temperature and humidity environment (40 ℃, 80% RH) causes notable performance deterioration, including reduced compressive strength and drastically elevated thermal conductivity. Materials with a moderate w/c ratio of 0.50 and a medium pore-size range of 1.0–2.5 mm provide the best balance among closed porosity, water absorption, compressive strength and hygrothermal deterioration resistance.

Acknowledgements

The present work was funded by Chongqing University Student Innovation and Entrepreneurship Project (S202510647024), the Natural Science Foundation of Chongqing (CSTB2025NSCQ-GPX0422) and the Science and Technology Research Program of Chongqing Municipal Education Commission of China (No. KJZD-K202501401).

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