

Synergistic Utilization of Recycled Fine Aggregates and Air-Entraining Agents in Alkali-Activated Concrete: Early-Age Strength Development under Subzero Temperatures and Freeze-Thaw Resistance

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Abstract

To overcome dual technical constraints—setting inhibition and freeze-thaw damage—in cold-region concrete construction while maximizing performance-cost efficiency, this study integrates alkali-activated slag concrete (AASC) and recycled fine aggregate (RFA) two green technologies, conducting comprehensive low-temperature performance investigations. Research examines early-age strength development under subzero conditions and long-term frost resistance at the strength stabilization stage. Air-entraining agents (AEA) were selected to counteract RFA-induced negative impacts through pore structure optimization, demonstrating the RFA-AEA synergy's dual influences on air-entrainment mechanisms and concrete strength. Key metrics—setting time, entrained air content, compressive strength, and relative dynamic elastic modulus—undergo systematic analysis. Critical findings reveal that:

(1) RFA significantly shortens setting time and impairs air-entraining efficacy, substantially reducing AASC workability. (2) Under low-temperature curing, AASC hydration depends primarily on alkali-activator dosage, exhibiting superior setting capability versus OPC based concrete. Early strength development correlates with initial raw material temperature; preheated and thermal protected 4% alkali-activator AASC rapidly achieves 5 MPa critical freezing damage threshold. (3) RFA promotes early strength via alkaline release-induced hydration compensation at low temperatures, but this effect diminishes with increasing alkali-activator dosage. Traditional air-entraining technology provides no significant early strength enhancement at -15°C. (4) While RFA-incorporated AASC still maintains excellent freeze-thaw resistance, excessive replacement ratios impair air-entrainers' pore-structure optimization capacity and weaken frost resistance improvements. At 50% replacement, RFA and air-entrainers demonstrate optimal synergistic compatibility in AASC, enabling concurrent early strength development and frost resistance, providing a sustainable low-carbon solution for winter concrete construction.

Highlights

- Systematic low-temperature experiments was conducted to address the distinct technical challenges presented during the early-age and strength stabilization stages of concrete.
- RFA accelerates setting while suppressing air-entrainment efficiency, synergistically inducing workability deterioration.
- RFA's inherent high alkalinity enhances autonomous setting behavior and strength development in AASC.
- Air-entraining agents are demonstrated to effectively counteract RFA-induced frost resistance attenuation.
- This investigation establishing a technical pathway for construction waste valorization and providing guidelines for cold-region concrete construction.

1 Introduction

Cold-region environments constitute approximately 22% of the global land area, encompassing high-latitude zones and high-altitude regions. These regions exhibit winter temperatures averaging below -15°C , necessitating construction interruptions exceeding 120 days. Concrete construction faces dual critical technical constraints: setting inhibition and freeze-thaw damage [1]. Ordinary Portland cement (OPC), the primary binder material, requires a minimum temperature of 5°C to sustain hydration. Under low-temperature conditions, significantly reduced hydration rates prolong the setting time of OPC concrete and delay strength development [2–4]. Below 0°C , free water in concrete undergoes phase transition to form ice crystals. Detrimental cracks initiate and propagate when frost damage stress exceeds the matrix tensile strength [5]. Mailvaganam et al. [6] demonstrated that fresh concrete freezing before setting reduces compressive strength by 20–40% and frost resistance by 40–60%. Consequently, implementing frost protection measures during concrete placement and curing is critical when ambient temperatures below 0°C . Conventional solutions include chemical admixtures and thermal curing methods. Inorganic salt antifreeze admixtures significantly depress freezing points but increase costs by 5–10% and induce steel corrosion risks, limiting their sustainability. Heated enclosure curing consumes substantial

resources during construction and operation. Temperature elevation from 5°C to 20°C generates daily CO₂ emissions of approximately 0.5 kg per cubic meter of enclosure volume, increasing curing costs by 20–30% [7, 8].

To develop innovative materials that eliminate reliance on external heat sources or chemical admixtures while enabling autonomous setting, hardening, and effective strength development under low-temperature conditions, alkali-activated slag concrete (AASC) exhibits significant inherent technical merits. Composed primarily of ground granulated blast furnace slag (GGBFS) and alkali-activators, AASC forms three-dimensional network gel structures through dissolution-polymerization reactions of silicon and aluminum compounds. This material is distinguished by its superior early-age strength and exceptional frost resistance [9], while exhibiting enhanced hydration kinetics and elevated heat release rates. Furthermore, the high concentration of free ions in the alkali-activator solution significantly depresses the freezing point of the liquid phase [10], providing an innovative pathway to overcome winter construction challenges. Compared to OPC based concrete, AASC exhibits shorter setting times and accelerated strength development, achieving 3-day compressive strengths 2.8–3.5 times higher than OPCC under identical conditions [11–13]. A compressive strength of 5 MPa is widely considered as the critical threshold to prevent early frost damage in concrete cured at low temperatures. Attaining this strength before pore water freezing effectively mitigates frost damage [14]. Furthermore, AASC demonstrates significant sustainable value and environmental benefits through solid waste resource utilization [15–22]. GGBFS, an industrial by-product of blast furnace ironmaking, serves as the primary binder material in AASC systems. As a sustainable substitute for OPC, its valorization significantly reduces carbon dioxide emissions from cement production. As the world's largest cement producer and consumer, China recorded a cement output of 2.3 billion tonnes in 2024 [23]. The associated CO₂ emissions significantly exacerbate greenhouse gas effects and atmospheric pollution. Concrete production incorporating GGBFS reduces CO₂ emissions by 7–10% compared to conventional systems by eliminating the high-temperature clinking process. This enables environmental burden allocation to the steel industry, achieving systemic optimization of the carbon footprint with 57–73% lower life cycle emissions than OPCC [24–26]. Furthermore, substantial industrial waste consumption in AASC production diverts landfill demand and mitigates heavy metal leaching risks [27–29].

Similar to AASC, recycled fine aggregate (RFA) constitutes a sustainable building material. In China, RFA is defined as particles smaller than 4.75 mm processed from concrete, mortar debris, or brick waste [30]. Direct utilization of construction waste for RFA production circumvents high-cost natural sand extraction and transportation processes, reducing production costs by as much as 20% compared to natural aggregates. Large-scale application fosters development of a circular economy chain for construction waste valorization, mitigating landfill accumulation while creating new economic value [31–33]. Furthermore, the chemical composition of RFA confers unique technical application advantages. XRF analysis reveals that the adhered aged mortar on RFA surfaces contains significantly higher CaO content compared to natural fine aggregates (NFA). Ju et al. [34] demonstrated that incorporating appropriate CaO enhances hydration heat release and optimizes the microstructure of concrete under low-temperature curing, improving mechanical properties. Effective setting is prerequisite for low-temperature concrete strength development. Previous research [35] revealed that RFA exhibits significant setting time reduction in alkali-activated slag mortar systems. Xiao et al. [36] identified NaOH molar concentration as a critical factor governing compressive strength enhancement. Unlike externally dependent approaches, RFA's inherent high alkalinity demonstrates substantial potential for enhancing AASC strength development under sub-zero conditions. Building on these findings, synergistic utilization of AASC and RFA yields triple environmental benefits: reducing carbon emissions by decreasing cement consumption, mitigating ecological damage from natural sand extraction, and reducing landfill occupation caused by construction waste accumulation.

While RFA provides economic benefits, it inevitably causes performance degradation. Compared to recycled coarse aggregate, systematic research on RFA remains insufficient. The attached cement pastes elevate concrete porosity, and therefore bring negative influence on the durability. In the practical application, the use of RFA in OPCC production is highly restricted or even banned under multiple national standards [37–38]. Research demonstrates that RFA exhibits reduced apparent density and elevated crushing index relative to NFA. At 100% replacement, splitting tensile strength decreases by

13.9% compared to control mixture [39]. At low RFA replacement levels, tensile strength may increase due to alkaline activation; Niu et al. [40] documented a 7% reduction in compressive strength at 50% RFA replacement. Under 100% replacement, compressive strength declines to less than 65% of NFA concrete [41–43]. AASC incorporating RFA exhibits elevated water absorption, inducing more pronounced strength deterioration during freeze-thaw cycles. Fan et al. [44] established that at 33% recycled aggregate replacement, concrete achieves frost resistance comparable to natural concrete. Liu et al. [45] improved freeze-thaw resistance in alkali-activated recycled concrete through fly ash modification and aggregate shaping; however, this strategy proves economically unsustainable for practical implementation. Krivenko et al. [41] optimized pore architecture via steam curing to enhance frost resistance in AASC, yet this method encounters implementation barriers during winter construction due to excessive energy intensity and stringent thermal control requirements, constraining engineering applicability.

To counteract performance degradation induced by RFA, Kang et al. improved concrete fatigue life and toughness by incorporating basalt fibers with varying volume fractions and lengths [46]. In contrast this study employs air-entraining agents (AEA) to optimize freeze-thaw resistance. As a conventional concrete admixture, AEA alleviate frost heave stress through the introduction of stable micrometer-scale bubbles, demonstrating particular efficacy in mass concrete projects within extreme cold regions [47]. Beyond stress mitigation, AEA refine pore structure and reduce capillary connectivity, significantly lowering water absorption to mitigate RFA-induced attenuation of freeze-thaw resistance [48–49]. Previous research fails to adequately characterize the factors governing strength development in AASC under sub-zero curing. The interaction between RFA's alkali-supplementing characteristic and low-temperature hydration inhibition remains unclear, while the functional mechanisms of air-entraining technology in alkali-activated recycled concrete systems necessitates further investigation.

To address these research gaps, this work integrates two sustainable construction materials to develop an AASC system incorporating RFA as an aggregate substrate. A systematic investigation of performance under sub-zero conditions was conducted, demonstrating the efficacy of this approach in overcoming dual technical constraints—setting inhibition and freeze-thaw damage—in cold-region concrete construction. Initially, based on setting time, air content, and compressive strength metrics, this study investigated the effects of RFA and AEA on air-entrainment efficiency, workability, and strength progression profiles in AASC systems; these findings established the foundation for engineering applications of AEA and RFA in AASC. Subsequently, focusing on the low-temperature performance during concrete strength development stage, the influence of AEA dosage, alkali-activator dosage, Thermal insulation schemes, and RFA replacement ratio on AASC under sub-zero conditions was systematically evaluated to determine factors governing initial setting behavior and Strength development kinetics in low-temperature environments. Ultimately, the synergistic mechanism of RFA and AEA on the long-term frost resistance of AASC at the strength stabilization stage was investigated through integrated analysis of mass loss rate and relative dynamic elastic modulus after freeze-thaw cycles, providing insights for enhanced durability performance.

2 Materials and methods

2.1 Raw materials

Ground granulated blast furnace slag (GGBFS) utilized in this study was Grade S95, procured from a mineral processing plant in Lingshou County, Hebei Province. Particle size distribution is presented in Fig. 1, with physical parameters detailed in Table 1 and elemental composition analyzed by XRF provided in Table 2. Grade 42.5 Ordinary Portland Cement (OPC), compliant with Chinese National Standard GB 175-2007, served as the binder in control mixtures.

Natural coarse aggregates (NCA) were selected as crushed gravel with a gradation of 5–10 mm, exhibiting an apparent density of 2,864 kg/m³ and a crush index of 2.09%. River sand served as the natural fine aggregates (NFA), demonstrating a density of 2,880 kg/m³ and a fineness modulus of 2.87. Recycled fine aggregates (RFA) derived from demolished construction waste in Harbin underwent crushing and screening processes; particles smaller than 4.75 mm were classified

as RFA, exhibiting a measured density of 2,380 kg/m³. To lower the impact caused by mismatches between particle size distribution, the quantity of RFA in each particle size range was selected same as that of the NFA. The resultant RFA particle size of RFA and NFA distribution are shown in Fig.2, while its physical parameters are summarized in Table 3, with Chemical composition detailed in Table 4. Chemical composition analysis revealed RFA contained higher CaO content compared to NFA, to evaluate alkaline component effects on concrete performance, pH measurements were conducted, with comprehensive data provided in Table 3. The air-entraining agent(AEA) employed was imported AE-200, manufactured by Takeomo Oil & Fat Co., Ltd. This transparent liquid admixture contains 20% solid content by mass. Dosage was controlled as a percentage of the total cementitious materials mass.

A combination of liquid sodium silicate (water glass) and solid sodium hydroxide (NaOH) was utilized as the alkali activator, with the preparation procedure detailed in Fig.3. The sodium silicate, produced in Hebei China, exhibited a modulus (SiO₂/Na₂O molar ratio) of 3.26, containing 8.57% Na₂O and 27.06% SiO₂. Laboratory-grade NaOH with a purity ≥99% was served to modulate the activator's modulus.

Table 1 GGBFS parameters

Activity		Specific surface area	specific gravity	L.O.I	water content	basicity coefficient
7d	28d	410m ² /kg	2.94	0.6%	0.01%	1.27
80%	98%					

Table 2 Chemical composition of GGBFS

Chemical composition	CaO	SiO ₂	Al ₂ O ₃	K ₂ O	Na ₂ O	Fe ₂ O ₃	MgO
Wt(%)	42.96	27.60	13.51	0.39	0.46	0.54	9.31

Table 3 parameters of RFA and NFA and NCA

	Density/kg/m ³	Water absorption/%	F.M.	PH	Crush index/%
RFA	2380	10.83	2.87	11.3	-
NFA	2880	2.11	2.87	7.8	-
NCA	2864	1.38	-	7.3	2.09

Table 4 Chemical composition of RS and RFA obtained by XRF analysis (wt%).

	CaO	SiO ₂	Al ₂ O ₃	K ₂ O	Na ₂ O	Fe ₂ O ₃	MgO
NFA	1.39	75.59	13.18	4.42	3.28	1.46	0.11
RFA	16.96	60.4	10.65	3.10	1.87	10.65	1.00

2.2 Mix proportions

Building upon established research [35], all mix proportions in this study maintained a fixed water-to-binder ratio of 0.5 and fine aggregate ratio of 40%,

Experimental variables comprised:RFA volumetric replacement ratios for NFA (0%, 50%, 100%), air-entraining agent dosages (0%, 0.3%, 0.5%), initial material temperatures (-15°C, 15°C), and early-age thermal protection after casting (thermal curing blankets/none). alkali-activator was pre-formulated and the modulus was adjusted to 1.0. In alignment with previous research, the dosage of alkali-activator was selected as 3%, 4%, and 6%.

Compressive strength tests after Low-Temperature curing were employed 100 mm concrete cubes, while flexural strength and freeze-thaw resistance tests utilized 100 mm × 100 mm × 400 mm specimens, with detailed mix proportions documented in Table 5, nomenclature system for specimens is schematically illustrated in Fig.4.

Table 5 Mix proportions [Unit:kg/m³]

Dosage of alkali-activator	Replacement ratio of RFA%	Dosage of Air-Entraining Agent	AEA	NCA	NFA	RFA	GGBFS	Water	Water glass	NaOH
3%	0	0	0	1150.60	767.06	0	350	141.49	52.06	13.02
		0.3%	1.05	1150.60	767.06	0	350	141.49	52.06	13.02
		0.5%	1.75	1150.60	767.06	0	350	141.49	52.06	13.02
	50	0	0	1128.79	376.26	376.26	350	141.49	52.06	13.02
	100	0	0	1107.80	0	738.53	350	141.49	52.06	13.02
4%	0	0	0	1150.60	767.06	0	350	130.32	69.41	17.36
		0.3%	1.05	1150.60	767.06	0	350	130.32	69.41	17.36
		0.5%	1.75	1150.60	767.06	0	350	130.32	69.41	17.36
	50	0	0	1128.79	376.26	0	350	130.32	69.41	17.36
		0.3%	1.05	1128.79	376.26	376.26	350	130.32	69.41	17.36
		0.5%	1.75	1128.79	376.26	738.53	350	130.32	69.41	17.36
	100	0	0	1107.80	0	0	350	130.32	69.41	17.36
		0.3%	1.05	1107.80	0	376.26	350	130.32	69.41	17.36
		0.5%	1.75	1107.80	0	738.53	350	130.32	69.41	17.36
6%	0	0	0	1150.60	767.06	0	350	107.98	104.12	26.04
		0.3%	1.05	1150.60	767.06	0	350	107.98	104.12	26.04
		0.5%	1.75	1150.60	767.06	0	350	107.98	104.12	26.04
	50	0	0	1128.79	376.26	376.26	350	107.98	104.12	26.04
	100	0	0	1107.80	0	738.53	350	107.98	104.12	26.04

2.3 Testing procedures

2.3.1 Preparing of specimens

Mixing of AASC was conducted in a temperature-controlled chamber maintained at $20 \pm 2^\circ\text{C}$. Aggregates were preconditioned to surface-saturated dry condition before mixing. The procedure commenced by dry-mixing aggregates and slag powder in a planetary mixer for 1 minute. Subsequently, pre-formulated alkali-activator solution and additional mixing water were charged into the mixer, followed by 2 minutes of wet mixing. The resulting mixture was cast into molds and compacted using a vibrating table. Specimens were immediately sealed with plastic membranes and subjected to designated curing regimes according to experimental requirements.

2.3.2 Compressive, flexural strengths

The compressive strength and flexural strength of AASC were tested in accordance with ASTM C39 and ASTM C496, respectively. The experimental configurations are schematically illustrated in Fig.5 and Fig.6. Compressive strength testing were performed at ages of 3, 7, and 28 days after casting, while flexural strength testing was conducted on day 28. Average results of three specimens were used for each testing age.

2.3.3 Slump, Setting time and Air content

Slump and air content were tested immediately after mixing in compliance with ASTM C143/C143M and ASTM C231, respectively. For setting time measurement, mortar samples were tested using a modified Vicat needle in accordance with ASTM C807.

2.3.4 Compressive Strength Test after Low-Temperature Setting and Curing

Before concrete mixing, raw materials were preconditioned under two temperature regimes: one batch was placed in a -15°C chamber for 24 hours to simulate winter outdoor storage (designated Group L, Low Temperature), while the other batch was conditioned in a 15°C temperature-controlled chamber for 24 hours to maintain temperature stability (designated Group H, High Temperature).

Immediately after casting, specimens from both groups were transferred with their molds to a -15°C low-temperature chamber to replicate the Setting and strength development conditions of alkali-activated concrete under severe winter temperatures.

Additionally, two groups were established based on Groups L and H. These specimens were wrapped with triple-layer thermal curing blankets to provide early thermal protection, designated as Group L+B and Group H+B respectively. They were subsequently transferred to the same low-temperature chamber for further curing. After curing at -15°C for 6 h, 24 h, and 120 h, specimens were sampled and tested for compressive strength in accordance with ASTM C39. The overall experimental procedure is schematically illustrated in Fig.7.

2.3.5 Freeze-Thaw Resistance Test

In accordance with GB/T 50082-2009, rapid freeze-thaw cycling tests were conducted on concrete specimens using an HDK-9 concrete rapid freeze-thaw apparatus. Specimens were cured at $20 \pm 2^\circ\text{C}/95\% \text{ RH}$ for 24 d, followed by 4 d of water immersion before initiating freeze-thaw cycles. Relative dynamic modulus (measured by Resonance Frequency Apparatus) and mass variation were evaluated at 25-cycle intervals, with each interval comprising 25 consecutive freeze-thaw cycles.

2.3.6 MIP and SEM-EDS test

The distribution of the pore size was determined by utilizing mercury intrusion porosimetry (MIP) test. Equipment of AutoPore IV-9500V 1.09 type mercury porosimeter with maximum pressure of 3300 psia was used for the MIP test. Approximately 10 g of each sample was core drilled from $100 \times 100 \times 100 \text{ mm}$ cubic specimen after curing at $20 \pm 2^\circ\text{C}$ and 95% RH environment for 28 days. After oven-drying at 60°C to constant mass, specimens underwent mercury intrusion under stepwise pressure increments within a sealed chamber, enabling porosity and pore radius quantification. Mortar

specimens (0% and 100% RFA) cured under identical conditions for 28 days were sectioned into 1–2 mm slices. These were ethanol-immersed to terminate hydration, vacuum-dried at 40°C for 24 h, and gold-sputtered prior to analysis.

Microstructural interfaces between RFA particles and AASC matrix were examined using a Zeiss Ultra Plus SEM operated at 5 kV, with secondary electron imaging at 5,000× magnification. EDS surface scanning was employed to conduct compositional analysis of the ITZ and mortar matrix regions in AASC.

3 Results and discussions

3.1 Setting time, Air content and slump

Fig.8 illustrates the effect of RFA replacement ratio on the setting time of alkali-activated slag mortar with a fixed alkali-activator concentration of 3%. The control specimen with 100% natural aggregates achieved final set at 57 minutes. With increasing RFA substitution levels, the mortar exhibited progressively accelerated setting behavior. Final setting times decreased substantially with higher RFA incorporation, showing an inverse correlation with replacement level. Specimens with 50% and 100% RFA replacement showed setting time reductions of 31.6% and 68.4%, respectively, compared to the 0% RFA mixture.

This accelerated setting primarily originates from the alkaline replenishment effect, wherein RFA functions as an additional alkali source in alkali-activated systems. Residual cementitious phases within RFA undergo dissolution under high alkalinity, releasing soluble Na^+/K^+ ions that augment the activator's alkalinity, significantly enhancing early hydration kinetics in alkali-activated slag matrices. At 100% RFA replacement, mortars achieve final set within 18 minutes—exhibiting ultra-rapid setting incompatible with conventional concrete application requirements. Consequently, mix design optimization through controlled RFA dosage is essential to modulate setting behavior for practical application.

Fig.9 demonstrates the impact of RFA replacement ratio on air-entraining efficiency in AASC. The air content of AASC mixtures exhibits an inverse correlation with increasing RFA replacement ratio. For 0% and 100% RFA replacement ratios, baseline air contents in fresh concrete without AEA measured 2.14% and 1.63%, respectively. This disparity primarily arises from RFA's high water absorption (>10.8%), which reduces the amount of free water available for bubble formation within the concrete paste, consequently leading to the observed gap in baseline air content. With 0.5% AEA addition, the NFA mixture attained 5.37% air content (3.23% increase), whereas the 100% RFA mixture exhibited only a 1.89% increment. These results demonstrate RFA compromises AEA efficacy due to residual impurity particles (such as hardened cement paste, clay minerals) that restrict micro-bubble formation space when incorporated at high replacement levels, thereby limiting air-entraining efficiency.

The slump variation of AASC incorporating varying RFA replacement ratios and AEA dosages is illustrated in Fig.10. Consistent with its effects on setting time and air content, RFA progressively reduces slump, consistent with its effects on setting time and air content. RFA accelerates the setting and hardening process of AASC, leading to a substantial increase in early-age mixture viscosity which consequently reduces slump. Although AEA-induced micro-bubbles partially restore fluidity via the ball-bearing effect, the air-entraining efficiency is significantly compromised at 100% RFA replacement, resulting in severe fluidity loss; the slump sharply decreases from 91 mm to 34 mm, representing a 62.64% reduction.

The synergistic interaction between the setting acceleration induced by RFA and its inherent air-entrainment suppression mechanism collectively contributes to this substantial slump reduction and impaired construction performance.

3.2 Mechanical properties

3.2.1 Compressive strength

As illustrated in Figs. 11a–11c, The compressive strength of AASC decreases with higher AEA dosage and RFA replacement ratios. This reduction primarily stems from dual interfacial transition zone within RFA-containing concrete—comprising old aggregate-old mortar and old mortar-new mortar interfaces. Unlike the single ITZ in NFA concrete, these dual ITZs exhibit higher microcrack densities, directly impairing aggregate-matrix interfacial bonding and serving as preferential failure sites. Increased RFA replacement ratios expand the quantity and dimensions of these dual ITZs, substantially diminishing mechanical performance.

A secondary mechanism involves AEA-induced micro-bubbles elevating concrete porosity and reducing effective load-bearing cross-sectional area. The combined effect of these two mechanisms—degradation at dual ITZs and reduced effective area due to entrained air—synergistically contributes to the deterioration of macroscopic mechanical properties.

Notably, while RFA incorporation reduces concrete strength, the AEA-induced strength degradation diminishes with higher RFA replacement levels. Experimental data show a 13.6% 28-day compressive strength reduction at 0% RFA with 0.5% AEA, decreasing to 7.4% at 100% RFA replacement. This phenomenon primarily relates to RFA's inhibitory effect on air entrainment. This attenuation primarily stems from RFA's suppression of air entrainment—at identical 0.5% AEA dosage, 100% RFA concrete achieved only 65.5% of the air content in NFA mixtures. The constrained air entrainment mitigates effective load-bearing cross-sectional area loss, thereby alleviating AEA-induced strength degradation.

The influence of RFA on AASC compressive strength development exhibits significant time-dependent evolution. Under standard curing ($20\pm 2^{\circ}\text{C}$, 95% RH), specimens showed negligible strength differences at 3 days—the 100% RFA group exhibited only 6.2% reduction versus natural aggregates. At 7 days of curing, natural aggregates demonstrated increasing strength advantage, with 100% RFA showing 14.5% reduction. As curing progressed, the detrimental effect of RFA on strength transitioned to predominance, culminating at 28 days where the 100% RFA group attained merely 79.1% of the compressive strength measured in the natural aggregate group.

This strength evolution pattern stems from the temporal competition between RFA's unique alkali-supplementing characteristic and the interfacial defects arising from dual ITZ. Unlike in OPC systems, RFA exhibits enhanced compatibility with alkali-activated slag binders due to intrinsic self-activation. RFA's elevated CaO content—primarily from adhered cement paste, this chemical composition is the primary factor of RFA's high alkalinity. During early curing, when slag hydration is incomplete, RFA-derived alkalis elevate effective activator concentration, accelerating hydration kinetics to compensate for ITZ defects and offset initial strength loss. As hydration progresses toward completion, RFA's alkali-supplementing capacity diminishes. Consequently, the weakened bonding characteristics at dual ITZ interfaces become the dominant contributor to performance evolution, accelerating long-term mechanical property degradation.

At low RFA replacement ratios, strength deterioration in AASC is limited. For instance, 50% RFA replacement achieves over 93% of the 28-day compressive strength relative to NFA control group. Conversely, 100% RFA replacement exhibits substantial deterioration with 21.9% strength reduction after 28 days. This phenomenon occurs because when the RFA replacement ratio is low, NFA constitute a larger proportion within the concrete. Consequently, the volume of the dual ITZs surrounding RFA particles is substantially smaller than the single ITZ of NFA. In this replacement ratio, RFA bears a lower load proportion compared to natural sand, while its inherent microcracks exhibit reduced potential to initiate strength deterioration. As a result, exerting negligible impact on ultimate strength.

At 100% RFA replacement, dual ITZ volume expands substantially. Absent natural fine aggregate spatial separation, adjacent RFA particles inevitably contact, causing interconnected dual ITZ networks. Consequently, a substantial portion of the applied load transfers directly through RFA, propagating microcracks that coalesce under sustained stress, reaching critical thresholds for matrix defect initiation.

Owing to RFA's alkali-supplementing capacity, AASC early-age strength development accelerates with increasing replacement ratios. At 50% RFA, 3-day compressive strength reaches 71% of 28-day strength, increasing to 80% at 100%

replacement. However, dual ITZ defects substantially deteriorate 28-day strength despite enhanced early performance, highlighting a temporal conflict between alkaline supplement effect and interfacial defects. Consequently, engineering applications require balancing early-strength advantages against long-term degradation through strategies like graded replacement, material modification, or process optimization.

3.2.2 flexural strength

As shown in Fig.12, the flexural strength of alkali-activated slag recycled air-entrained concrete exhibits parallel degradation to compressive strength, decreasing significantly with higher AEA dosage and RFA replacement ratios. Although the underlying degradation mechanism aligns with that of compressive strength deterioration, it is critical to emphasize that when the AEA dosage increases, the reduction magnitude in flexural strength is substantially greater than that in compressive strength. For instance, the AASC4-0-0.5 mixture (0% RFA, 0.5% AEA,) exhibited 28.1% 28-day flexural strength loss, attributable to flexural fracture's heightened sensitivity to micro-bubbles and interfacial defects.

At RFA replacement ratios $\leq 50\%$, flexural strength reduction is marginal, exceeding 93% of natural fine aggregate (NFA) group values. However, 100% replacement induces significant deterioration with 17.5% 28-day flexural strength loss. As established in compressive strength analysis, this stems from cumulative effects at high replacement ratios: increased dual ITZ density, micro-crack proliferation, and weakened aggregate-matrix bonding. Under flexural loading, accelerated defect evolution promotes fracture network connectivity, causing precipitous performance loss.

3.3 Compressive Strength Test after Low-Temperature Setting and Curing

Compressive strength development at -15°C with varying alkali-activator dosage and air-entraining admixture dosage is presented in Fig.13a–13b, demonstrating that alkali-activator dosage is the predominant governing factor for early-age strength. As demonstrated in Fig.14a–b, at -15°C , both 3% alkali-activator and OPCC groups failed to achieve initial setting after 12 hours, exhibiting insufficient strength to permit demolding. In contrast, 6% alkali-activator specimen achieved 11.6 MPa compressive strength within only 6 hours.

This pronounced difference fundamentally stems from severely suppressed reaction kinetics at -15°C . Low temperatures drastically reduce hydration rates and cementitious product formation, while diminishing molecular kinetic energy and increasing pore solution viscosity, thereby impeding ion migration. Consequently, slag particles undergo insufficient activation, failing to produce effective reaction products. This critically compromises the structural coherence of the gel network through impaired particle densification and defective gel distribution. Thus, without thermal protection, neither 3% AASC nor OPCC achieves effective setting and strength development under -15°C conditions.

At 4% alkali-activator dosage, AASC exhibits restricted low-temperature setting capability, with compressive strength below 1.6 MPa,—strength development remains insufficient. Critically, after 120 hours curing, strength fails to attain the critical threshold against freezing damage. The underdeveloped fragile gel framework cannot withstand ice crystal expansion pressures, resulting in irreversible strength damage during later curing stages.

Elevating alkali-activator dosage to 6% significantly enhances early strength development in AASC, achieving 10 MPa within 6 hours—exceeding the 5 MPa critical freezing damage threshold. This elevated dosage facilitates rapid slag dissolution kinetics at low temperatures, promoting consumption of free water through intensified reaction processes. Consequently, freezable water content decreases significantly. The resulting robust hydration products demonstrate sufficient mechanical resilience to withstand cryostatic pressures induced by water-ice phase transformation. Thus, at 6% activator concentration, AASC effectively overcomes low-temperature reaction inhibition without thermal protection, achieving practical setting while satisfying construction strength requirements for extreme cold environments.

After 6 hours at -15°C, compressive strength development in AASC specimens (3%, 4%, 6% alkali-activator dosage) significantly decelerates, indicating hydration reactions become thermodynamically inhibited, with reaction kinetics effectively approaching cessation. This limitation arises from internal water freezing at critical low temperatures, where ice encapsulation of slag particles blocks ion transport pathways, interrupting hydration and impeding early strength development.

AEA does not improve early low-temperature setting performance in AASC. Sub-zero conditions induce ice crystal formation from free water, generating disruptive expansion pressure that damages the nascent cementitious matrix before sufficient strength development. Although entrained air voids provide spaces accommodating partial volumetric swelling, the resulting stress still initiates microcracks and interconnected pores, leading to strength degradation.

As demonstrated in Fig.15a–15c, three AASC mixtures (3%, 4%, 6% alkali-activators) were studied to assess activator dosage, initial material temperature, and thermal protection effects on strength development at -15°C. Results show that at 3% activator dosage, no thermal protection method achieved the 5 MPa critical freezing strength threshold. Both Group L (low-temperature materials) and Group L+B (L materials with blankets) failed initial set at -15°C, with L+B specimens sustaining demolding damage despite thermal protection. Although Group H (preheated materials) exhibited significantly enhanced strength compared to Group L, it remained below the 5 MPa threshold. Thus, 3% activator AASC is unsuitable for winter construction.

At 4% alkali-activator dosage, Group L AASC specimens exhibited marginal low-temperature setting capability without thermal protection, showing negligible strength improvement over 3% mixtures. Conversely, Group H+B (preheated materials with blankets) achieved 5 MPa critical freezing strength threshold within 6 hours at -15°C, indicating enhanced early-age freezing resistance. Elevating activator concentration to 6% ensured robust early strength development: Group L attained 11.8 MPa compressive strength in 6 hours—exceeding 5 MPa—enabling effective low-temperature setting without thermal protection.

These findings demonstrate that early-age strength development in AASC cured at -15°C is significantly governed by raw material initial temperature. Optimizing initial thermal protection effectively enhances AASC setting performance, but single thermal protection yielded limited strength gains: Group L+B (low-temperature materials with blankets) showed minimal improvement (<1 MPa) versus Group L. However, synchronous implementation of material preheating and thermal protection produced observable strength enhancement.

As shown in Fig.16a–16c, nine AASC mixtures (3%, 4%, 6% alkali-activators; 0%, 50%, 100% RFA) under H+B thermal protection were studied to assess RFA's impact on low-temperature strength development. RFA replacement enhances early-age setting performance at -15°C, with higher replacement ratios progressively accelerating strength development. However, this effect diminishes at elevated activator dosage. For AASC with 3% alkali-activator dosage, specimens containing 50% RFA achieved strength gains of 30.0% at 6 hours, 33.4% at 24 hours, and 13.8% at 120 hours relative to the 100% natural sand group, while demonstrating improvements of 59.9%, 57.1%, and 27.6% after corresponding curing time compared to the 100% RFA specimens.

While RFA enhances low-temperature strength development in AASC with low activator dosages, specimens failed to attain 5 MPa after 120 hours at -15°C. Following transfer to standard curing (20±2°C, 95% RH) for 23 days, compressive strength reached only 60.3% of fully standard-cured specimens, demonstrating severe early frost damage in the 3% activator group.

Low-temperature conditions inhibit hydration reactions, while melted ice crystals reduce matrix compactness through pore formation. Additionally, cryostatic pressure induces proliferation and expansion of microcracks within dual interfacial transition zones (ITZs). Consequently, specimens exhibit permanent strength deficits despite curing temperature recovery.

At 4% alkali-activator with 100% RFA replacement, strength enhancement versus AASC3-100-0 decreased to 25.5% (6h), 25.9% (24h), and 15.9% (120h). After 5 days at -15°C, specimens transferred to standard curing (20±2°C, 95% RH) achieved ~90% of fully standard-cured strength at 28 days, demonstrating minimal early freezing damage impact on long-term performance. Thus, 4% activator AASC with RFA develops considerable early freezing resistance.

AASC with 6% alkali-activator exhibits significantly enhanced early strength at -15°C without thermal protection, maintaining sustained hydration kinetics. After 5-day low-temperature curing followed by standard curing (20±2°C, 95% RH) for 23 days, 28-day compressive strength retention reached 95% versus fully standard-cured specimens. Notably, RFA incorporation provided marginal strength enhancement ($\leq 1\%$) across all stages.

3.4 Freeze-Thaw Resistance Test

As demonstrated in Fig.17a–17d, AASC exhibits superior freeze-thaw resistance over OPCC. Without AEA, the least frost-resistant AASC mixture (AASC4-100-0) exhibited only 4.37% mass loss and retained 85.5% relative dynamic elastic modulus after 300 freeze-thaw cycles, with structurally intact surfaces retaining legible markings (Fig.18b–18c). In contrast, the OPC based concrete (OPC-0-0) failed at 150 cycles, showing 5.74% mass loss, 56.7% residual modulus, and severe surface scaling with structural disintegration (Fig.18a).

This performance divergence originates from distinct hydration microstructures. OPC based concrete primarily forms C-S-H gel and $\text{Ca}(\text{OH})_2$ crystals that establish interconnected capillary pore networks. During freezing, cryostatic pressure from water-ice expansion exceeds pore wall fracture strength, initiating microcracks. As Fig.19-a shows, OPC based concrete specimens developed distinct aggregate-matrix cracks after 100 freeze-thaw cycles, indicating significantly diminished confinement capacity of the matrix toward aggregates. Subsequent crack propagation (Fig.19-b) penetrated matrix gel after 175 cycles, causing structural disintegration manifested as lamellar spalling.

AASC hydration products comprise dense calcium silicate gel (C-A-S-H) with predominantly closed gel pores <10 nm. The gel forms a dense nano-network via three-dimensional cross-linking. After 100 freeze-thaw cycles, as shown in Fig.19-c ITZ maintain structural integrity without crack initiation, demonstrating superior aggregate-matrix bonding compared to OPC systems, effectively inhibit the initiation and expansion of frost heave cracks.

After 300 freeze-thaw cycles, AASC4-0-0 was sampled and tested. At this time, the scale of micro-cracks has developed to a certain level, and the dense three-dimensional hydrated calcium silicate gel has been penetrated by cracks, as shown in Fig.19-d. At this time, the surface of the specimen has obviously peeled off, but it has not failed (relative dynamic elastic modulus > 85 %, mass loss rate < 4.5 %).

AASC freeze-thaw resistance varies significantly with increasing RFA replacement ratios. Specimens with 100% natural aggregates (AASC4-0-0) exhibited negligible mass loss during the first 100 freeze-thaw cycles, only after exceeding 100 cycles could a marginal increase in mass loss be observed. In contrast, AASC4-100-0 specimens with 100% RFA exhibited accelerated freeze-thaw deterioration. Significant mass loss emerged after 50 cycles, indicating that matrix damage had reached a critical threshold where microscopic defects transitioned to macroscopic failure. Progressive microcrack propagation and coalescence culminated in 1.8% mass loss at 100 cycles, confirming RFA increases freeze-thaw susceptibility and accelerates microcrack initiation.

Progressive freeze-thaw cycling intensified mass loss in AASC4-100-0, widening performance gaps with AASC4-0-0 and highlighting RFA's frost resistance deficiency. This deterioration stems from internal damage accumulation during freeze-thaw stages, where cryostatic stresses propagate microcracks along RFA's dual ITZs (Fig.19-e). Resultant cracks penetrate the C-A-S-H gel matrix, compromising aggregate interfacial restraint and establishing surface scaling as the dominant failure mechanism.

AEA dosage significantly regulates AASC freeze-thaw resistance, evidenced by marked improvements in mass loss ratio and relative dynamic modulus with increasing content. This confirms AEA effectively mitigates frost resistance deterioration induced by RFA. For the NFA group (AASC4-0-0), AEA demonstrated excellent void-forming performance but marginal freeze-thaw resistance enhancement due to AASC's inherently superior frost resistance. The low porosity of natural aggregates and simpler ITZ region reduced defect susceptibility, thereby diminishing the potential for significant freeze-thaw performance gains through air entrainment.

At 50% RFA replacement, AEA demonstrates compensatory efficacy for RFA: Specimens with 0.5% AEA (AASC4-50-0.5) exhibit significantly enhanced freeze-thaw resistance versus non-AEA controls after 300 cycles, reducing relative dynamic elastic modulus loss from 13.36% to 6.48% (51.4% reduction) and mass loss from 3.1% to 1.39% (55.1% reduction). This efficacy arises as RFA-induced dual ITZs increase matrix structural complexity, partially compromising freeze-thaw resistance. Under these conditions, the pore structure refinement mechanism of AEA is realized through measurable frost durability enhancement. SEM analysis of AASC4-50-0.5 specimens (Fig. 19-f) revealed that the AEA introduced numerous voids measuring 50-200 μm in diameter within the AASC matrix. These voids significantly mitigated cryostatic pressure during freeze-thaw cycling. Although partial pore wall fracturing occurred after 300 cycles, intact air-voids structures remained observable, demonstrating that the specimens retained measurable freeze-thaw resistance functionality at the microscopic level.

At 100% RFA replacement, RFA-induced performance degradation outweighs AEA's freeze-thaw resistance enhancement due to the mechanism similar to the previously described RFA-induced deterioration of air-entrainer efficacy. Specifically, increased paste viscosity and restricted bubble formation space diminish air-entrainers' pore optimization effectiveness.

Consequently, at 50% replacement ratio, AEA achieve optimal synergistic compatibility with RFA—substantially reducing concrete production costs while offsetting the performance degradation induced by RFA, thereby significantly enhancing the freeze-thaw resistance of AASC.

3.5 Microstructure analysis

3.5.1 Interfacial transition zone SEM-EDS test

Table 6 Elemental composition of ITZ

Weight percentage	Region 1	Region 2	Region 3	Region 4	Region 5
Ca	7.03	45.8	6.62	52.37	43.11
Si	49.76	30.37	47.94	17.87	28.70

Fig. 20a–20b present scanning electron microscopy (SEM) images of ITZs between aggregates and mortar matrix in specimens AASC4-0-0 and AASC4-100-0. Energy-dispersive X-ray spectroscopy (EDS) analyses at marked points reveal distinct compositional signatures, with elemental compositions tabulated in Table 6.

In the specimen (AASC4-0-0), Region 1 exhibits a silicon (Si) content of 49.76% and calcium (Ca) content of 7.03%, with significantly predominant Si concentration relative to Ca, confirming its identity as natural fine aggregates. Region 2 exhibits 45.80% Si and 30.37% Ca, with Ca proportionally exceeding Si—characteristic of slag hydration products. In AASC4-100-0, Region 3 shows 6.62% Ca and 47.94% Si, compositionally analogous to Region 1, establishing its designation as the core material of RFA. Region 4 displays 52.37% Ca, nearly triple its Si content (17.46%), signifying it is surface-adhered old mortar on recycled aggregates. Region 5 exhibits Si content comparable to Region 2, characterized as slag hydration products. Collectively, these findings reveal compositional distinctions between natural and

recycled aggregates while elucidating the interaction mechanisms between slag hydration products and residual mortar in recycled materials systems.

SEM analysis reveals natural aggregate specimens exhibit a relatively dense, low-porosity microstructures, while RFA systems display distinct interfacial gaps between RFA and the alkali-activated slag matrix, predisposing them to localized detachment during freeze-thaw cycling. This compromised bonding, combined with pre-existing microcracks in RFA, induces stress concentrations that propagate cracks and accelerate deterioration—establishing dual ITZs as critical weaknesses in AASC. This microstructural mechanism fundamentally explains the mechanical performance degradation with increasing RFA replacement ratios.

3.5.2 Microscopic pore structure analysis

Concrete pore classification follows the International Union of Pure and Applied Chemistry (IUPAC) framework [37], with detailed categorization provided in Table 7. This system defines three pore categories: micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm)—the latter classified as capillary pores. Experimental studies consistently confirm that pores exceeding 50 nm detrimentally compromise concrete's macro-scale properties, particularly strength and durability.

Table 7 IUPAC pore size classification

Pore description	Radius (nm)	Diameters (nm)	Harmful or not
Micropores	<1.25	<2.5	Harmless
Mesopores	1.25–25	2.5–50	Less harmful
Macropores	25–5000	50–10000	Harmful
Entrained air voids, entrapped air voids, preexisting microcracks	5000–50000	10000–100000	Seriously harmful

MIP tests was employed to characterize the pore structure of AASC specimens with varying RFA replacement ratios, with pore size distribution curves presented in Fig.21. Within the ≤ 10 nm pore size range, the 0% RFA specimen exhibits the highest peak, indicating greater mercury intrusion and relatively larger pore volume within this range. Compared to specimens with pure NFA, RFA incorporation significantly increases porosity in the 10–100 nm mesopore range, following a decreasing order of 100% RFA > 50% RFA > 0% RFA. For pores >100 nm, all three mixtures demonstrate highly similar porosity distribution patterns—a phenomenon primarily attributed to micropores in old mortar, inherent defects in RFA, and microcracks within dual ITZs.

RFA incorporation shifts pore distribution peaks toward larger diameters, with 50% and 100% RFA specimens peaking at ~21 nm. At 50% RFA replacement, mesopore (10–100 nm) volume increases by approximately 90% compared to the NFA group. Pores within this size range primarily belong to the mesopore category, and their volumetric expansion partially accounts for the reduced freeze-thaw resistance induced by RFA. Water-saturated mesopores effectively act as preferential ice-nucleation sites at low temperatures, accelerating crack propagation along pore chains [38]. Specimens with 100% RFA exhibit further mesopore volume growth beyond 50% RFA levels, correlating directly with enhanced freeze-thaw performance degradation.

Table 8 Results of MIP tests

	Total intrusion volume (mL/g)	Mediam pore diameter (nm)	Average pore diameter (4V/A, nm)	Porosity (%)
0	24.071	18.5	13.7	17.2315
50	28.212	26.3	18.8	20.0433
100	29.677	28.5	19.0	21.7452

Table 8 presents the pore structure characteristics of AASC with varying RFA replacement ratios. As the RFA replacement ratio increases, concrete porosity progressively rises—exhibiting 17.2% for the NFA group and 20.04% for the 50% replacement group, representing a 2.8% increase. This pronounced pore structure evolution primarily stems from RFA incorporation substantially reducing free water content and paste volume in the mixture, resulting in insufficient paste to fill inter-aggregate voids. Concurrently, hydration is suppressed, hindering hydration products formation and compromising matrix densification. Furthermore, RFA's inherent porosity significantly contributes to elevated AASC porosity at higher replacement levels.

Increasing RFA replacement from 50% to 100% elevates porosity to 21.7%, a marginal 1.7% increase indicating attenuated porosity evolution. Under this mix proportion, the alkali-supplementing capacity becomes fully pronounced at high replacement levels. Alkaline substances within RFA undergo substantial dissolution and release, functionally equivalent to elevated activator dosage. This mechanism accelerates the early-stage C-A-S-H gel formation. Although high RFA dosage significantly reduces the setting time of alkali-activated slag mortar and adversely impacts concrete workability to some extent, the pore structure degradation induced by RFA is effectively counteracted. This micro mechanism mitigates impediments to hydration gel formation caused by free water depletion.

RFA incorporation under 100% replacement induces simultaneous elevation of porosity and coarsening of pore size distribution in AASC. Elevated macropore proportions (100–5000 μm) critically contribute to compressive strength reduction and freeze-thaw resistance deterioration. Additionally, both medium pore diameter and average pore diameter exhibit marginal increases under this elevated replacement ratio, further evidencing the compensation mechanism. This indicates that the alkaline supplement effect of RFA at high replacement levels partially counteracts its degradation effects on pore structure, achieving a degree of dynamic equilibrium in pore configuration.

At 50% RFA replacement, medium pore diameter increases by 42%, indicating elevated microcrack density and frost heave sensitivity. Microcracks and ITZs collectively form freeze-thaw vulnerable zones, where cracks propagate preferentially through ITZs during cycling, coalescing into macro-spalling that accelerates mass loss. This synchronized pore diameter-porosity growth elucidates RFA's frost resistance compromise mechanism. In contrast, the 0% RFA control group in AASC demonstrates effective crack propagation suppression owing to natural aggregates' low porosity and superior interfacial bonding capacity.

4. Conclusions

(1) The incorporation of RFA significantly reduces the setting time of alkali-activated slag, with 50% and 100% RFA replacement decreasing setting time by 31.6% and 68.4%, respectively, compared to NFA group, indicating accelerated early hydration in AASC. RFA incorporation substantially reduces air content in concrete mixtures, while concurrently diminishing air-entraining efficiency. Although AEA marginally increase concrete slump, this enhancement diminishes with higher RFA replacement ratios; under the dual influences of accelerated setting and suppressed air entrainment, AASC exhibits a pronounced nonlinear decline in slump as RFA replacement increases, with 50% and 100% RFA reducing slump by 38.3% and 61.7%, respectively.

(2) Increasing the RFA replacement ratio leads to declining trends in both compressive and flexural strengths of AASC specimens, with 50% and 100% RFA reducing 28-day compressive strength by 7.7% and 21.9%, and 28-day flexural strength by 7.0% and 17.5%, respectively. Notably, 3-day compressive strength exhibits no significant deterioration with RFA incorporation. Increased RFA replacement accelerates early-age strength development, enabling specimens to achieve higher proportions of their 28-day strength at early stages.

(3) The incorporation of AEA increases concrete air content, reducing the effective load-bearing area of AASC and consequently diminishing compressive and flexural strengths. A 0.5% AEA dosage reduces the 28-day compressive strength of natural fine aggregate AASC systems by 13.6%, while flexural strength demonstrates greater sensitivity to air-entrainer content, exhibiting a more substantial reduction of 28.1%. Notably, the magnitude of strength degradation induced by AEA diminishes with increasing RFA replacement ratios.

(4) The low-temperature hydration of AASC is predominantly governed by alkali-activator dosage. A 6% activator concentration enables specimens to achieve 11.6 MPa compressive strength within 6 hours at -15°C —exceeding the critical strength against freezing damage (5 MPa)—whereas mixtures with 3% activator and ordinary Portland cement controls fail to set even after 24 hours. AEA do not improve low-temperature setting performance, providing no strength enhancement for AASC under sub-zero conditions; Frost damage recovery capability exhibits significant gradation with increasing activator concentration, demonstrating that elevated alkali dosage effectively counteract microdefects induced by low-temperature setting and curing.

(5) Low-temperature cured early-age strength is critically governed by raw material initial temperature, with thermal protection efficacy exhibiting activator concentration thresholds: even H+B thermal protection (preheated materials + blankets) fails to achieve the 5 MPa critical strength for 3% activator systems. RFA provides low-temperature hydration compensation in 3–4% alkali systems via alkaline dissolution (50% RFA enhances 3% system strength by 30% at 6h), but this attenuates sharply with higher alkalinity ($\leq 1\%$ gain at 6%). Thus, 6% systems suit extreme cold unprotected scenarios, 4% systems demand 50–100% RFA with thermal measures, and 3% systems lack low-temperature adaptability.

(6) AASC exhibits significantly superior freeze-thaw resistance compared to OPCC, The dual ITZs introduced by RFA accelerate freeze-thaw damage progression AEA demonstrate an optimal synergistic range for regulating AASC frost resistance, a synergistic formulation combining $\leq 50\%$ RFA replacement ratio with 0.5% AEA dosage achieves balanced resource utilization and enhanced frost durability.

(7) SEM-EDS tests reveals the microstructural mechanism of RFA at ITZs in AASC, Dual ITZs comprising RFA cores and surface-adhered old mortar layers—the latter displaying high-calcium characteristics markedly distinct from slag hydration products. Pre-existing microcracks within old mortar induce stress concentration under load, establishing dual ITZs as weak point that fundamentally govern mechanical and freeze-thaw deterioration with increasing RFA replacement ratios.

(8) MIP tests reveals the pore-structure regulation mechanism of RFA in AASC: Increasing RFA replacement ratios significantly elevate porosity and induce coarsening of pore size distribution. Specimens with 50% and 100% RFA exhibit primary pore peaks shifting toward larger diameters, accompanied by increased proportions of macropores (100–5000 μm). While the alkaline supplement effect of RFA mitigates further pore deterioration at high replacement levels, defects from expanded dual ITZs remain the dominant factor governing mechanical and durability degradation. Practical engineering thus necessitates optimizing RFA replacement ratios ($\leq 50\%$) to strike a balance between pore structure refinement and performance requirements.

Declarations

Credit author statement

Rubo Shi: Experimental investigation, Data curation, Methodology, Formal analysis, Writing- original draft. Hua Yuan: Investigation, Data analysis. Kefei Shi: Data analysis. Feiyang Zhang: Investigation, Data analysis. Yan Yao: Review and Editing. Qin Lv: Review and Editing. Lange Zhang: Review and Editing. Shunli Yang: Review and Editing. Bangbang Wang: Review and Editing. Yang Gao: Investigation, Writing-review & editing. Jinguang Huang: Writing-review & editing, Investigation, Formal analysis, Validation and Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

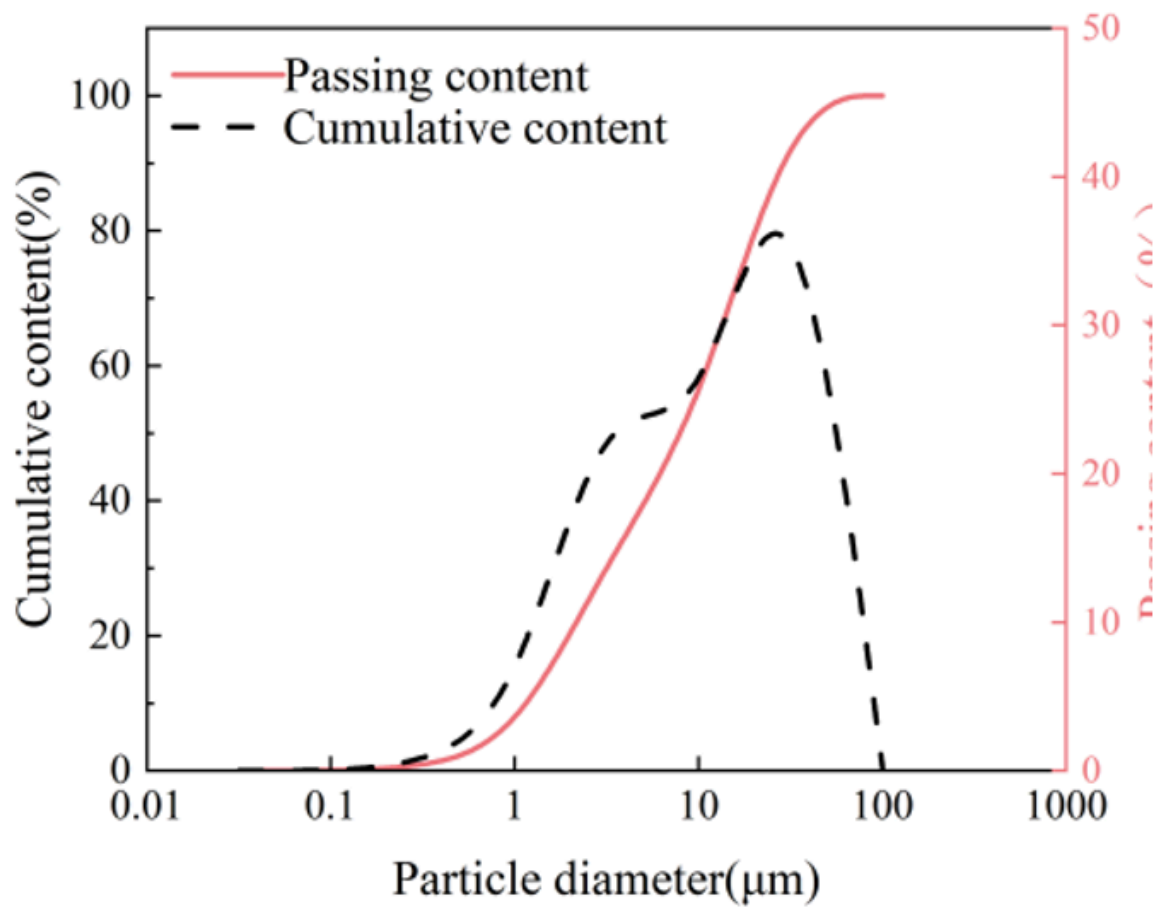


Figure 1

Particle size distribution of GGBFS

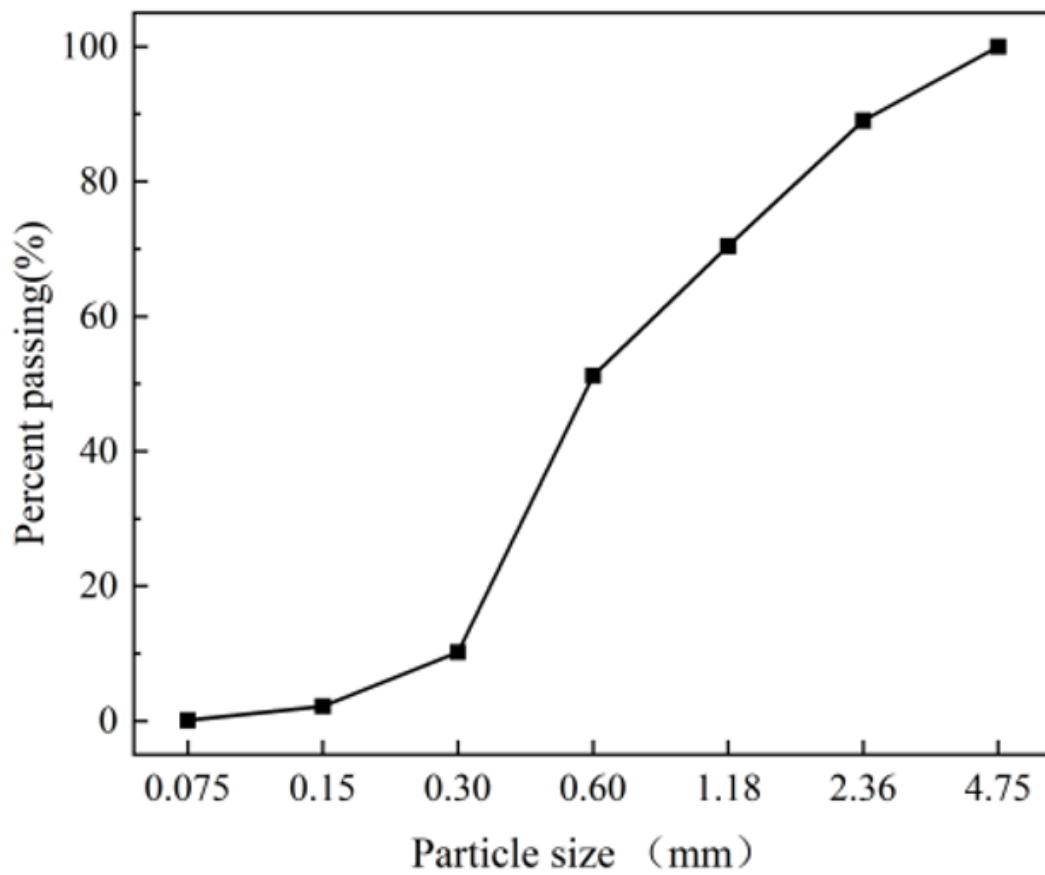


Figure 2
Particle size distribution of RS and RFA
(RFA is the same as RS after selected)

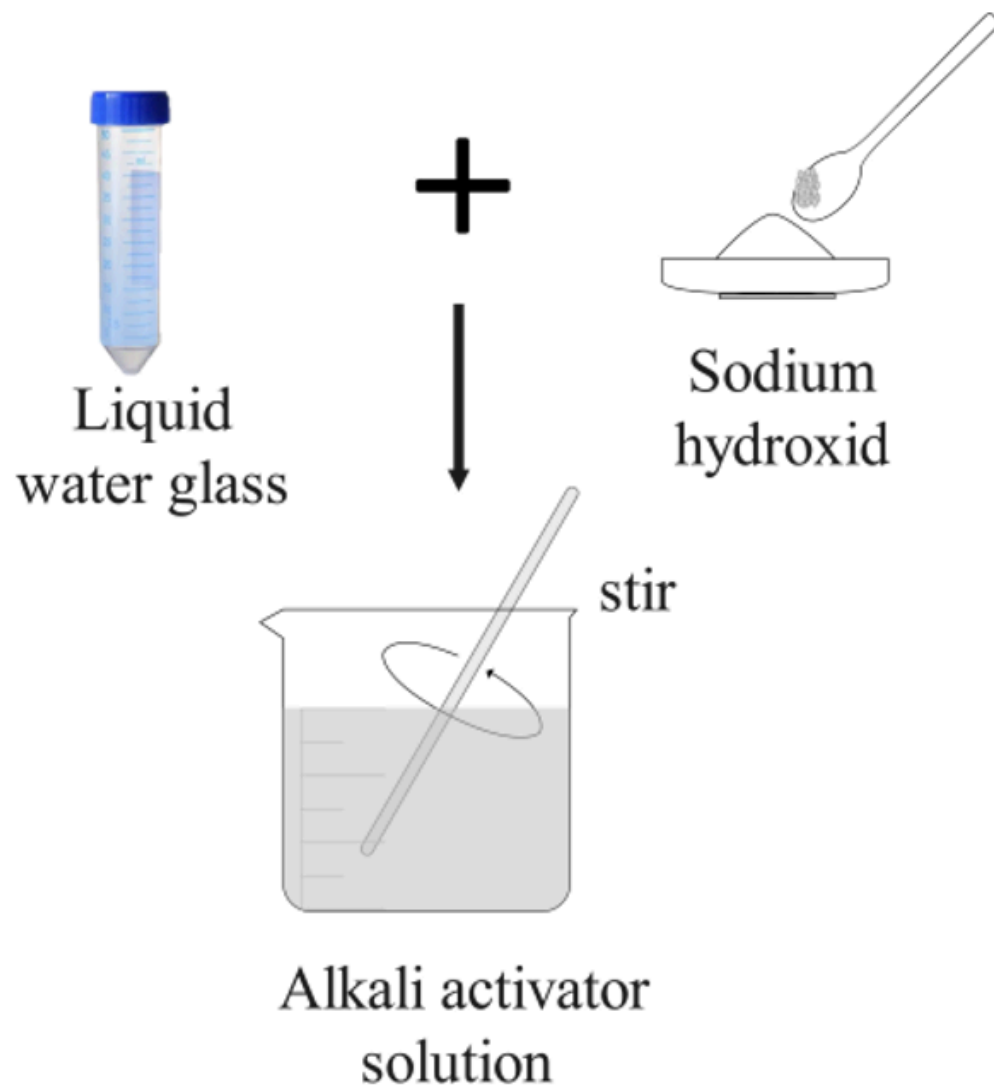


Figure 3

The preparation of Alkali-activator solution

AASCX-X-X

Dosage of the alkali-activator

RFA replacement rate

Dosage of Air-entraining agent

Figure 4

Nomenclature for Specimen Numbering

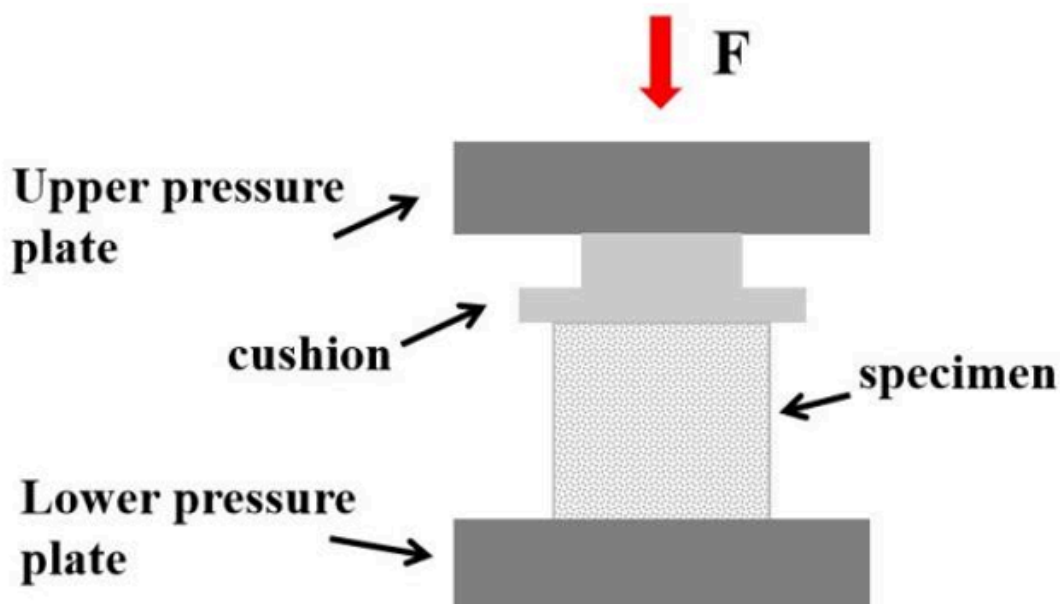


Figure 5

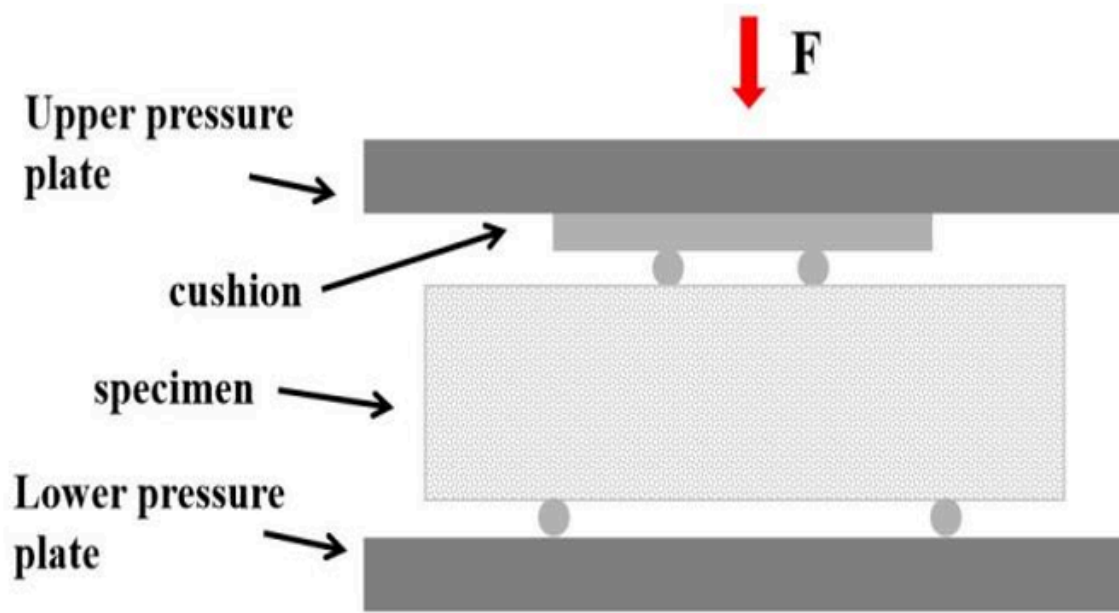


Figure 6

Bending test

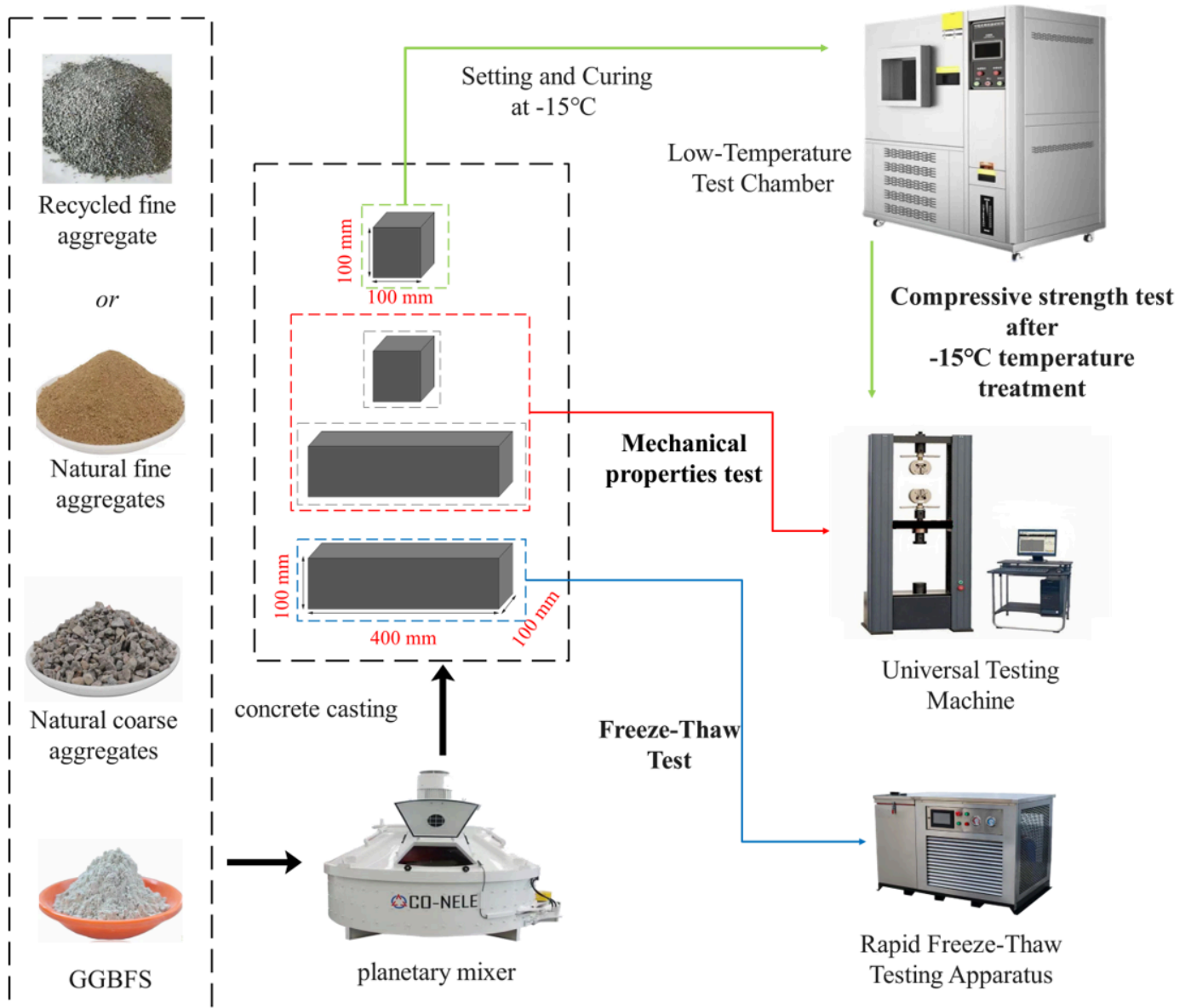


Figure 7

Experimental flow chart

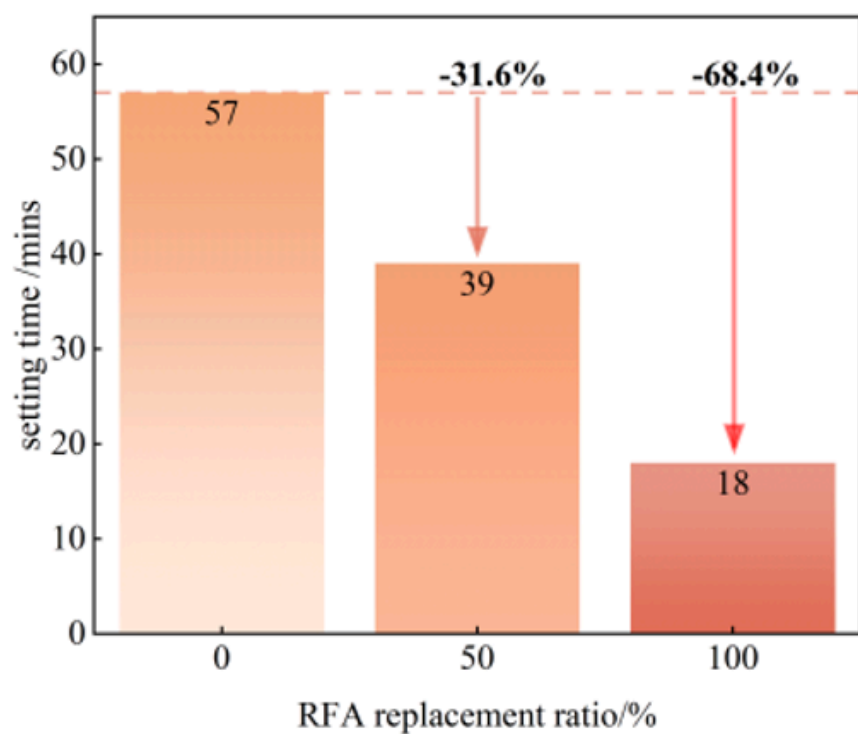


Figure 8

Setting time of Alkali-activated slag mortar with various replacement ratio of RFA

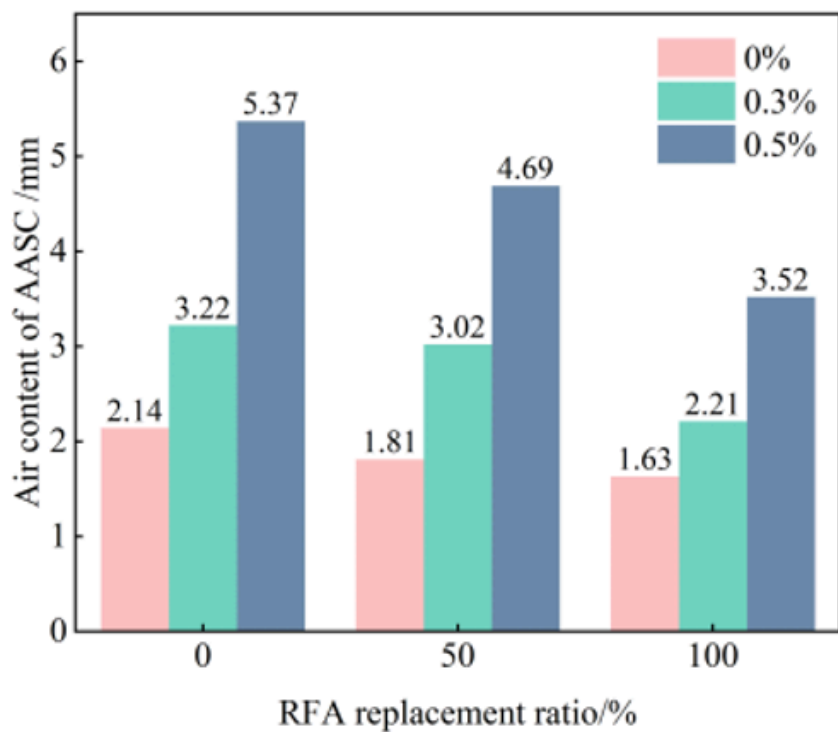


Figure 9

Air content of AASC with various replacement ratio of RFA and Dosage of AEA

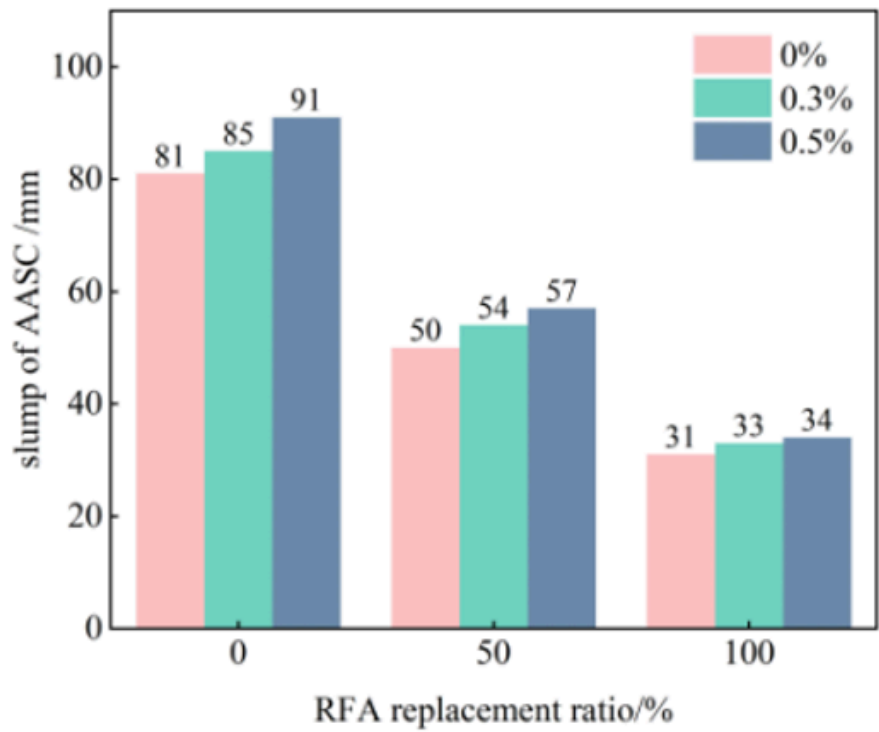


Figure 10

Slump of AASC with various replacement ratio of RFA and Dosage of AEA

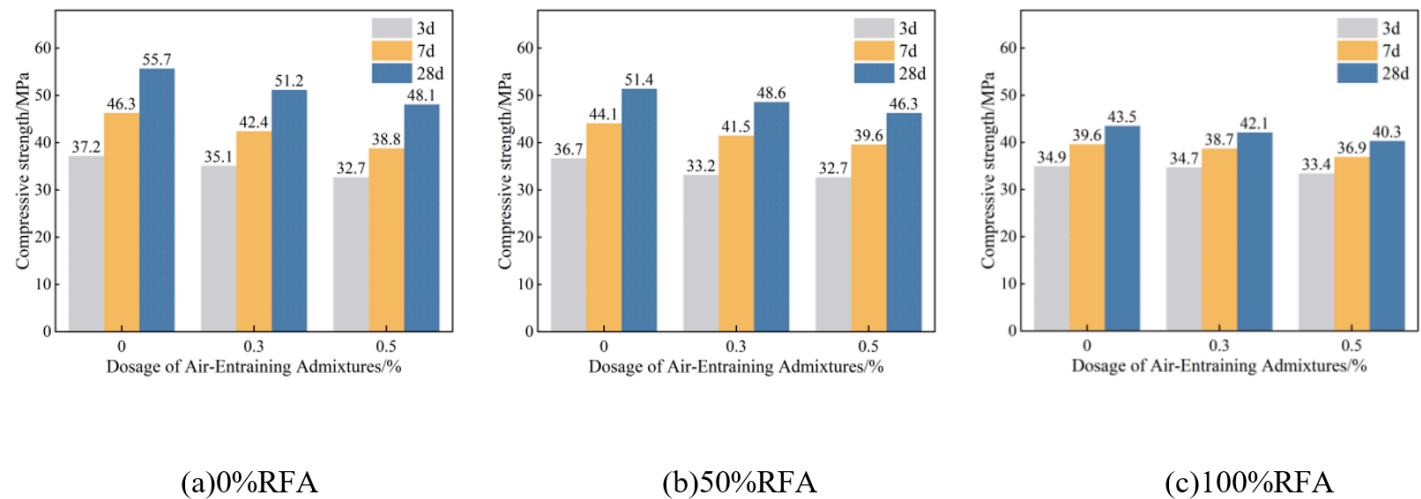


Figure 11

Compressive strength of alkali-activated concrete in different replacement ratios and AEA dosage

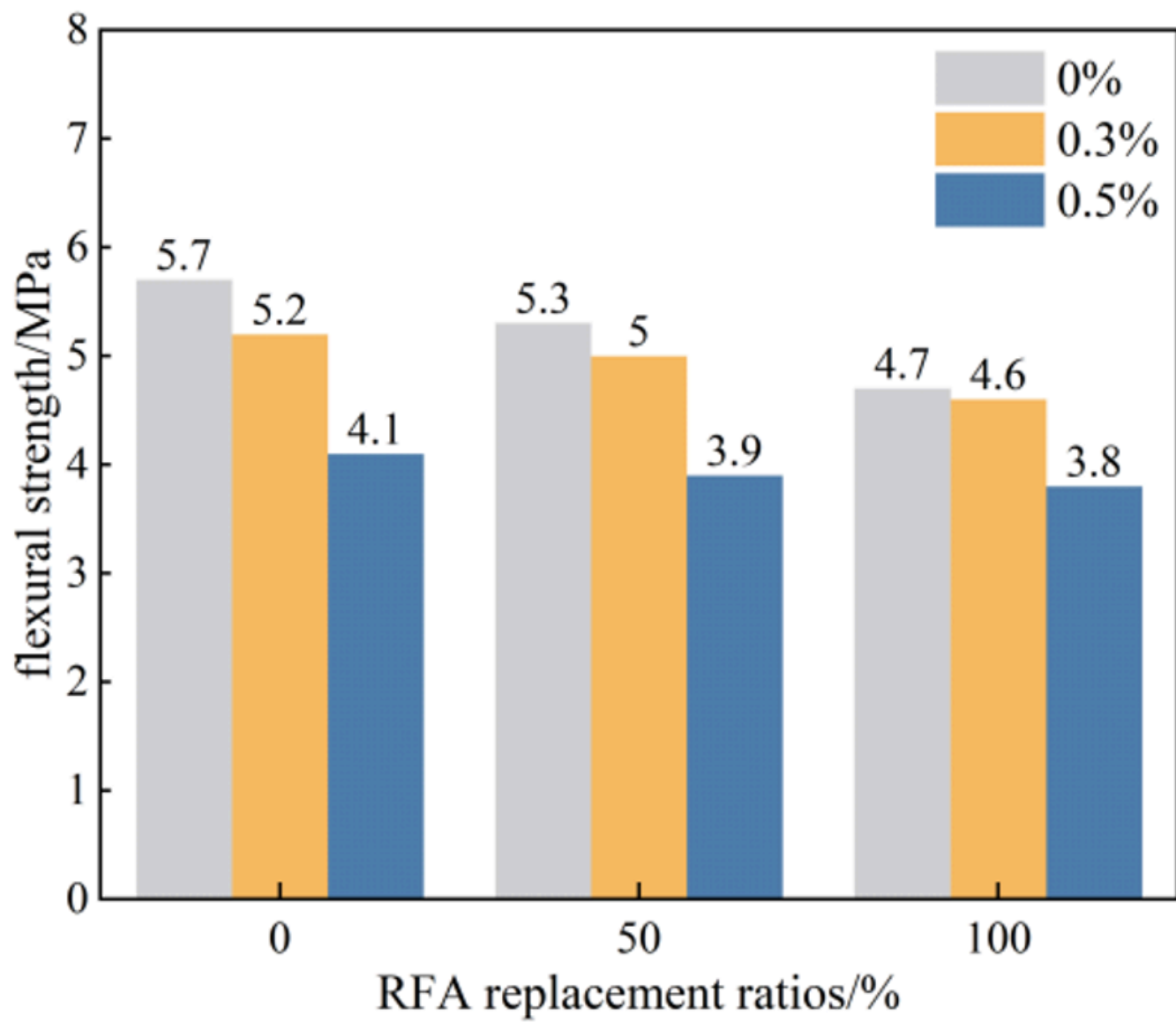
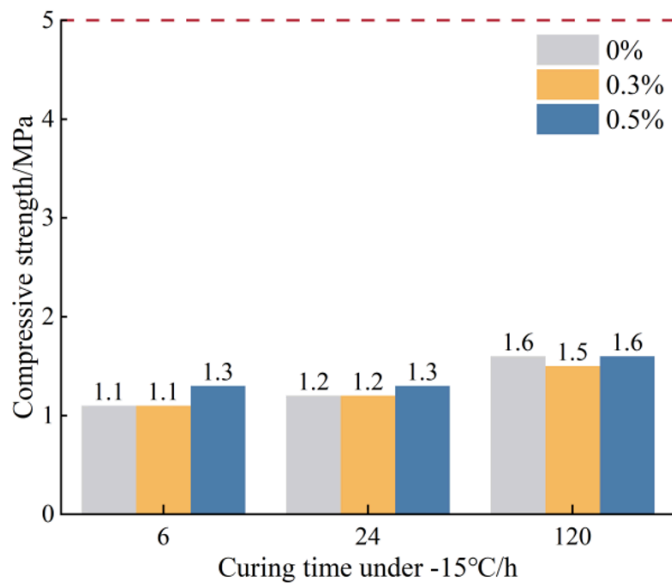
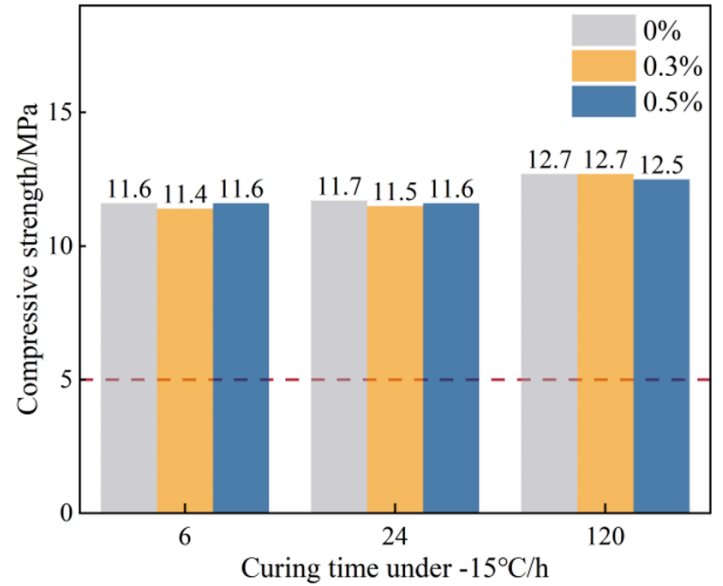


Figure 12

28d flexural strength



(a) 4% alkali-activator dosage



(b) 6% alkali-activator dosage

Figure 13

Compressive strength development at -15°C with varying alkali-activator dosage and air-entraining admixtures dosage



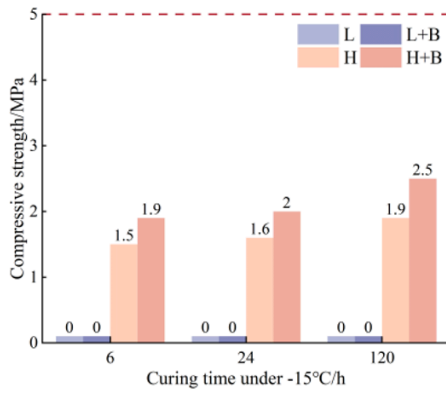
(a) OPCC



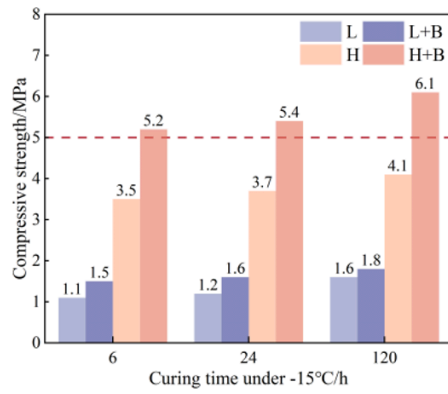
(b) AASC of 3% alkali-activator dosage

Figure 14

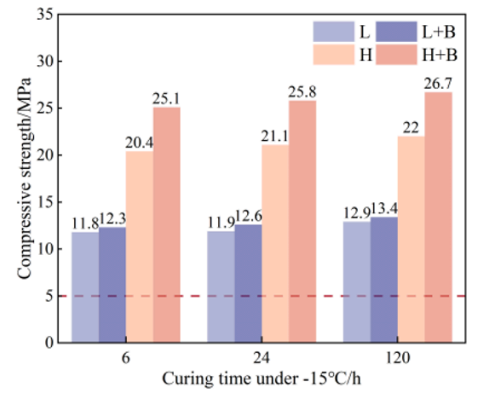
Setting behavior of OPCC and 3% alkali-activator dosage AASC specimens after 24h -15°C curing



(a)AASC3-0-0



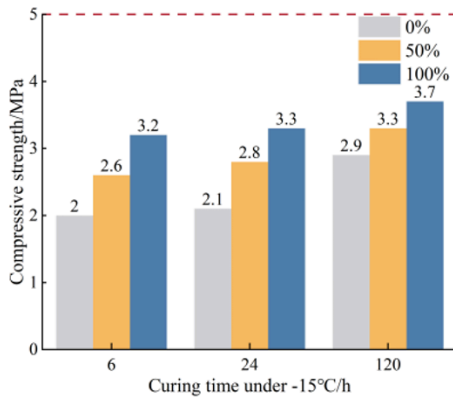
(b)AASC4-0-0



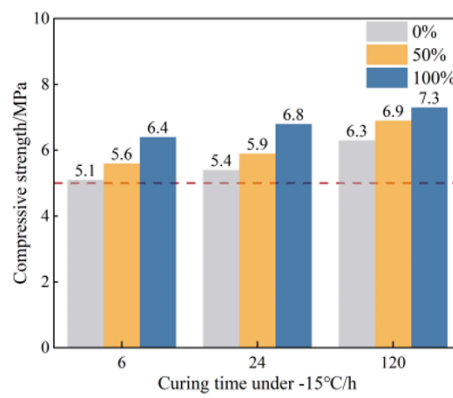
(c)AASC6-0-0

Figure 15

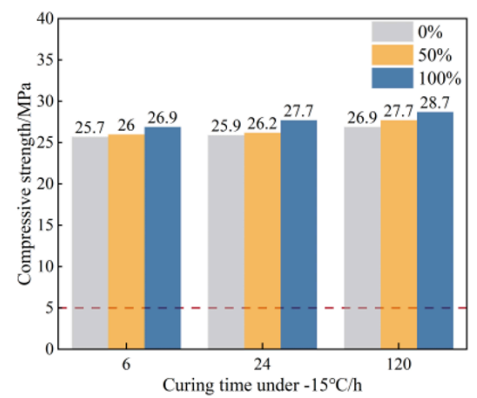
Compressive strength development at -15°C with various Dosage of alkali-activator and thermal insulation methods



(a)3%



(b)4%



(c)6%

Figure 16

Compressive strength development at -15°C with various Dosage of alkali-activator and Replacement ratios of RFA

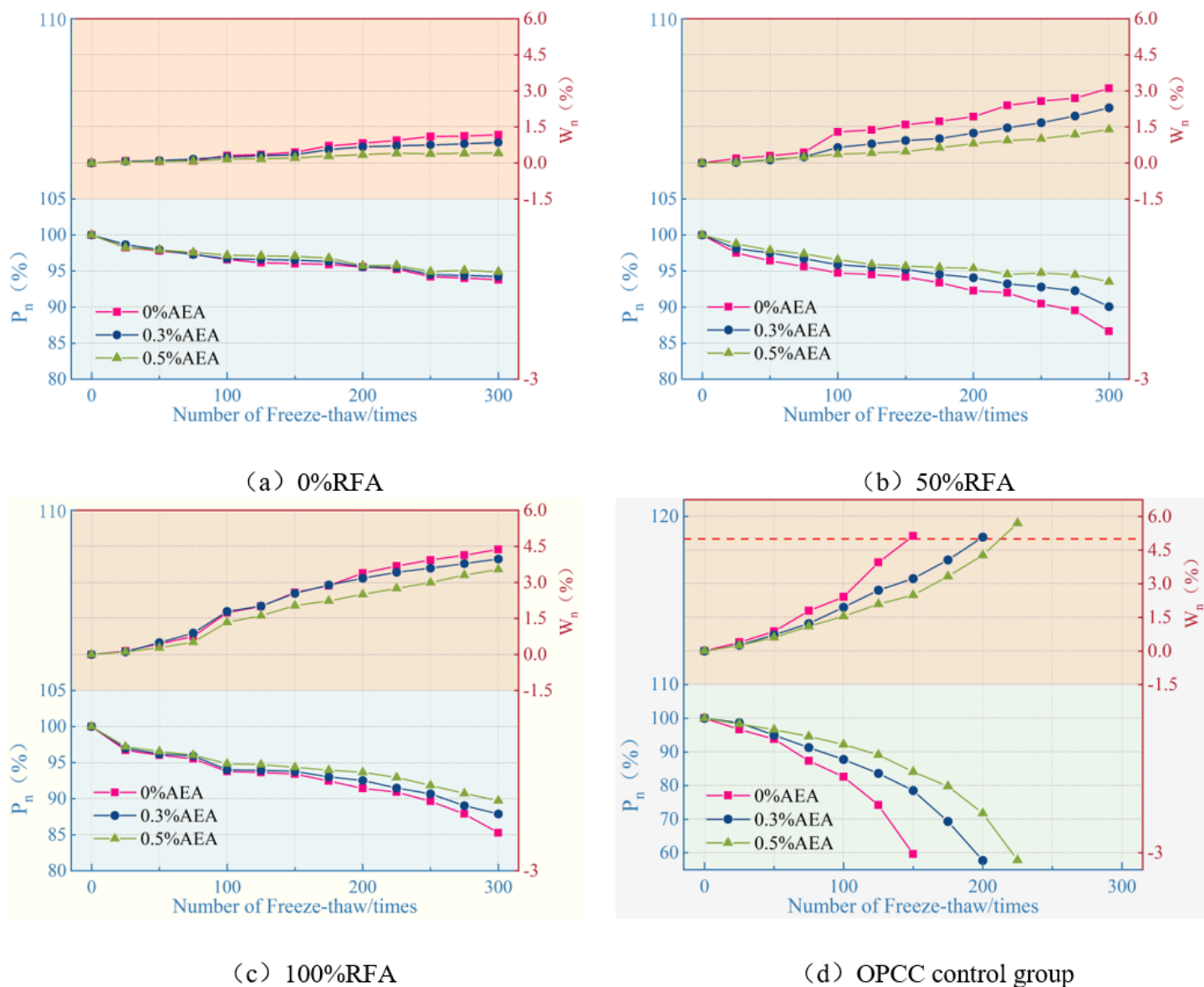


Figure 17

P_n and W_n of AASC with various Replacement ratios of RFA and air- entraining agents dosage

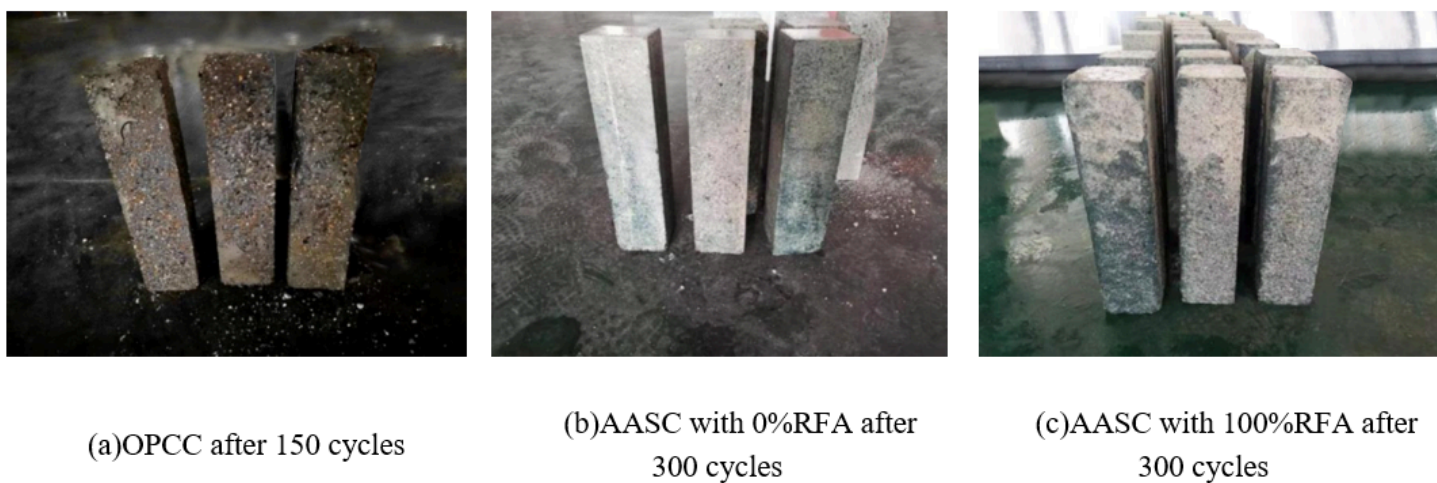


Figure 18

Apparent condition of specimens after different numbers of freeze-thaw cycles

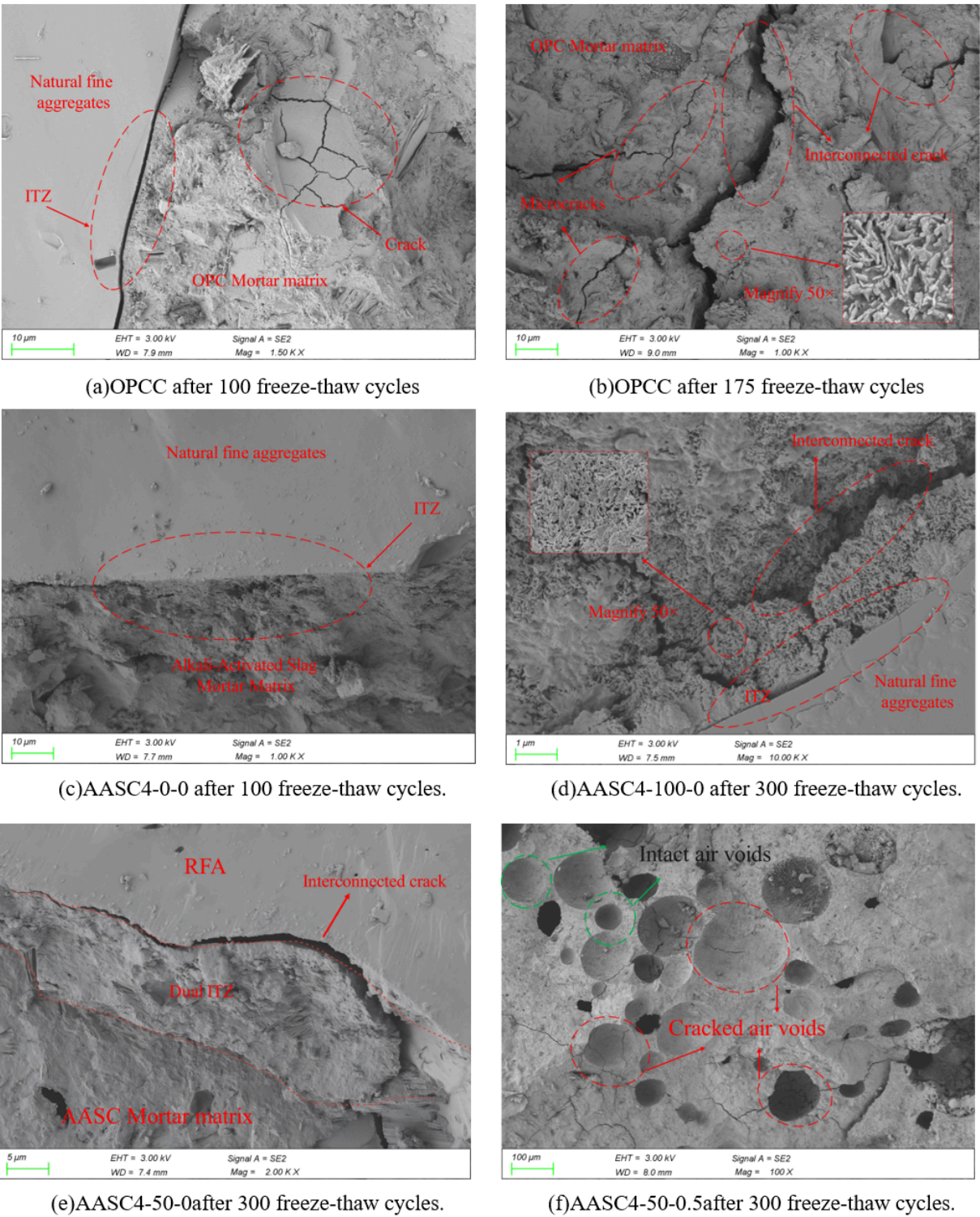
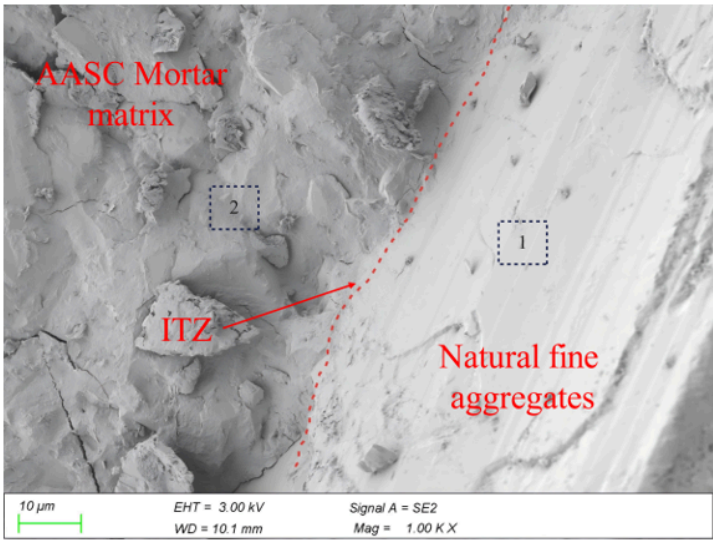
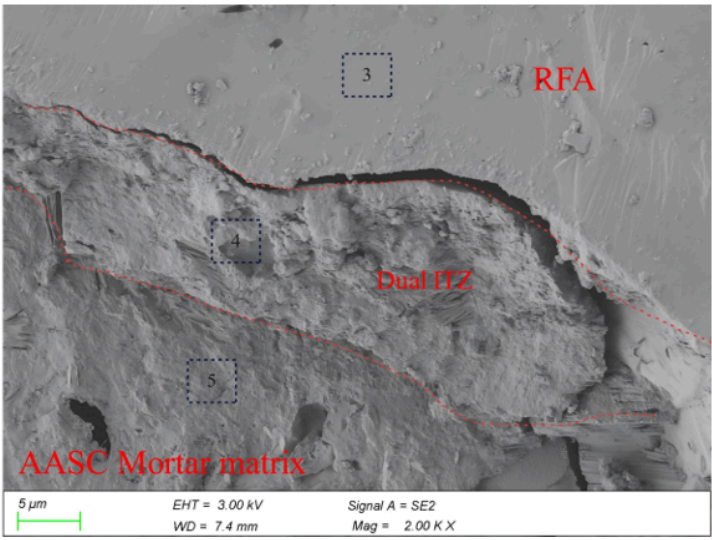


Figure 19

SEM images of mortar matrix and interfacial transition zones after different numbers of freeze-thaw cycles



(a) NFA ITZ morphology



(b) RFA ITZ morphology

Figure 20

ITZ morphology

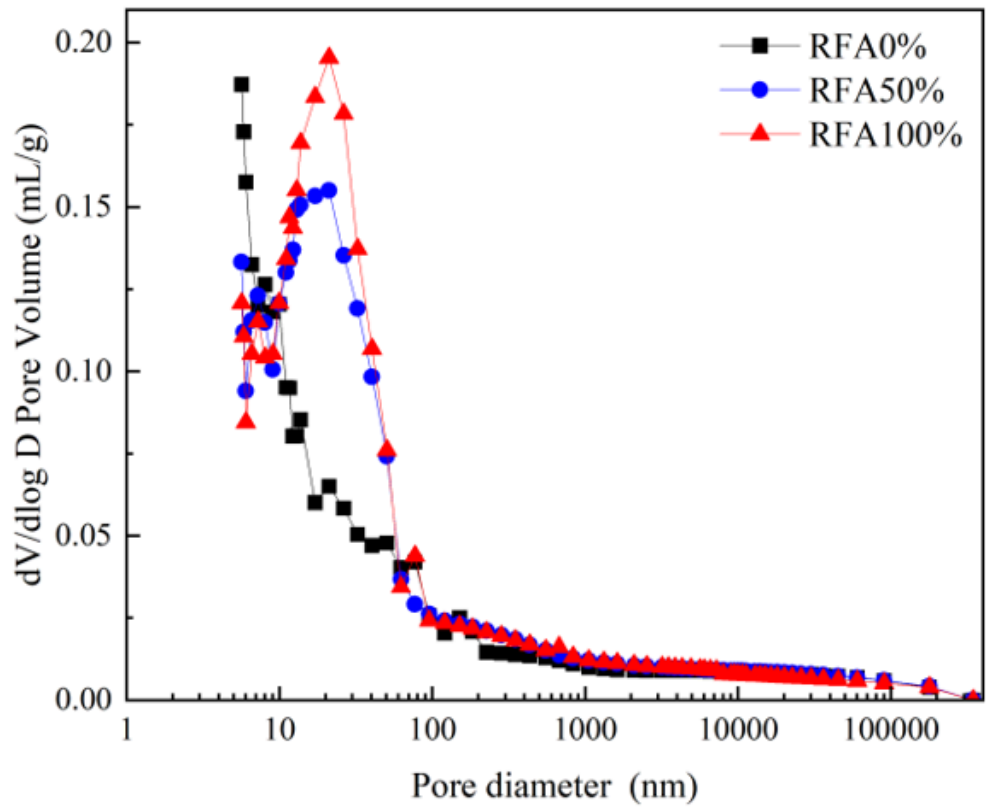


Figure 21

Pore size distribution