



Article

Development of Non-Autoclaved Aerated Concrete Incorporating Rice Husk Ash-Derived Silica and Polypropylene Microfibers for Sustainable Construction

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Abstract

The present study investigates the development of non-autoclaved aerated concrete (NAAC) incorporating rice husk ash (RHA)-derived amorphous silica, polypropylene microfibers, and a polycarboxylate-based superplasticizer to improve mechanical performance and durability while maintaining low density and thermal conductivity. Experimental investigations included density, compressive strength, thermal conductivity, water absorption, X-ray diffraction (XRD), microstructural observations, and TG-DTA analysis. The developed compositions containing 5–7% RHA and 0.10–0.20% polypropylene microfibers achieved compressive strength values of 4.5–4.8 MPa at densities of 520–560 kg/m³, which are comparable to or higher than values commonly reported for non-autoclaved aerated concrete of similar density. Thermal conductivity decreased to 0.12–0.13 W/(m·K), while water absorption was reduced to 15–18%. XRD, microstructural, and TG-DTA analyses suggested enhanced hydration reactions and improved development of the cementitious matrix due to pozzolanic interaction between amorphous silica and calcium hydroxide. The incorporation of polypropylene microfibers was associated with improved structural homogeneity of the developed NAAC compositions, whereas the superplasticizer enhanced mixture homogeneity and pore stability. The results suggest that the combined use of agricultural waste-derived silica and fiber reinforcement provides an effective approach for producing sustainable and energy-efficient NAAC without autoclave curing.

Keywords: non-autoclaved aerated concrete; rice husk ash; amorphous silica; polypropylene microfibers; pozzolanic reaction; pore structure; TG-DTA analysis; lightweight cementitious composites



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1. Introduction

The construction industry is increasingly oriented toward sustainable materials with reduced environmental impact and lower carbon emissions. Aerated concrete is widely used due to its low density and thermal insulation properties; however, conventional autoclaved aerated concrete (AAC) requires energy-intensive steam curing, which significantly increases production costs and environmental burden [1]. Cement production itself

is responsible for a considerable share of global CO₂ emissions, further motivating the development of alternative materials [2].

Non-autoclaved aerated concrete (NAAC) has emerged as a promising alternative due to its reduced energy consumption and simplified production process [3]. Nevertheless, NAAC systems often exhibit lower compressive strength, higher shrinkage, and less stable pore structures compared to autoclaved materials, which limits their structural applications [4]. The formation and stability of the pore system remain key challenges influencing both mechanical and thermal performance [5].

To overcome these limitations, recent research has focused on the use of supplementary cementitious materials (SCMs), particularly those derived from industrial and agricultural waste. Rice husk ash (RHA) is considered one of the most effective SCMs due to its high amorphous silica content and strong pozzolanic reactivity [6–9]. The silica present in RHA reacts with calcium hydroxide to form additional calcium silicate hydrate (C–S–H), leading to improved microstructure and strength development [10].

Several studies have confirmed that the incorporation of RHA enhances compressive strength and reduces permeability in cement-based materials [11]. In addition, RHA contributes to pore refinement and densification of the cement matrix, which is critical for improving durability [12–14]. The utilization of agricultural waste such as rice husk ash also supports sustainable waste management and reduces environmental pollution [15,16].

Recent studies specifically addressing aerated concrete systems have shown that the incorporation of RHA leads to reduced density and improved thermal insulation properties due to its low specific gravity and porous structure. Furthermore, experimental investigations demonstrate that optimal replacement levels of RHA can enhance strength while maintaining lightweight characteristics. These findings highlight the strong potential of RHA in the development of sustainable aerated concrete.

In parallel, fiber reinforcement has been widely used to improve the mechanical performance of cementitious composites. Polypropylene fibers are particularly valued because of their chemical stability and flexibility [17–19]. According to previous studies, polypropylene fibers have been reported to improve the post-cracking behavior of cementitious composites [20,21]. Moreover, recent studies have reported that polypropylene fibers may contribute to improved durability and resistance to aggressive environments in cement-based composites.

The combined use of rice husk ash and polypropylene fibers has also been investigated in sustainable concrete systems. It has been shown that optimal proportions of RHA (around 15%) and polypropylene fibers ($\approx 0.25\%$) lead to improved mechanical performance and environmental benefits. However, excessive replacement levels may negatively affect strength, indicating the need for optimized compositions.

Another critical factor in aerated concrete production is the formation of a uniform pore structure. Aluminum powder is commonly used as a gas-forming agent, producing hydrogen gas through reaction with calcium hydroxide [22,23]. The characteristics of the resulting pore system directly influence density, thermal conductivity, and mechanical strength [24].

The rheological properties of fresh mixtures also play a crucial role in achieving homogeneous pore distribution. Polycarboxylate-based superplasticizers are widely used to improve workability and reduce water demand [25,26]. These admixtures enhance mixture stability and contribute to uniform pore formation, which is especially important in non-autoclaved systems [27,28].

Recent review studies emphasize the growing interest in utilizing waste materials in aerated concrete production to improve both performance and sustainability. However, most of these studies focus on either autoclaved systems or individual material components.

Despite the extensive research on RHA, fiber reinforcement, and chemical admixtures separately, their combined application in non-autoclaved aerated concrete remains insufficiently explored. The combined application of rice husk ash, polypropylene microfibers, and polycarboxylate superplasticizers remains insufficiently explored in NAAC systems.

Furthermore, the use of locally available raw materials such as dune sand remains underutilized, despite its potential for reducing material costs and environmental impact [29].

Based on the literature review, the following gaps are identified:

Lack of studies on combined RHA + polypropylene fiber systems in NAAC.

Insufficient understanding of pore structure stabilization without autoclaving.

Limited research on the combined effects of SCM, fiber reinforcement, and superplasticizer. Underexplored use of local raw materials (dune sand).

Therefore, the aim of this study is to develop a high-performance non-autoclaved aerated concrete incorporating rice husk ash-derived silica and polypropylene microfibers. The study evaluates the influence of these components on density, compressive strength, thermal conductivity, and water absorption, as well as the mechanisms responsible for performance enhancement.

2. Materials and Methods

In this study, locally available and industrial materials were used to develop non-autoclaved aerated concrete (NAAC).

Portland cement CEM I 42.5N produced by Standard Cement LLP, Shymkent, Kazakhstan. The cement complied with the requirements of EN 197-1 and exhibited standard mechanical properties suitable for structural applications.

Dune quartz sand obtained from a local deposit was used as the siliceous filler. Prior to use, the sand was dried and ground in a ball mill to achieve a specific surface area of approximately 250–300 m²/kg, ensuring improved reactivity and uniform particle distribution.

Hydrated lime with an active CaO content of 70–85% was incorporated to promote the formation of calcium hydroxide necessary for gas formation and pozzolanic reactions.

Gypsum (CaSO₄·2H₂O) was added as a setting regulator to control the hydration kinetics of the binder system.

Amorphous silica derived from rice husk ash (RHA) with a SiO₂ content of 85–95% was used as a supplementary cementitious material. The ash was obtained by controlled combustion of rice husk, followed by grinding to enhance its pozzolanic activity.

A polycarboxylate-based superplasticizer was used to improve workability and reduce water demand. Polypropylene microfibers with a length of 6–12 mm were introduced as a reinforcing component in the investigated NAAC compositions.

Aluminum powder (PAP-1 or PAP-2 grade) was used as a gas-forming agent to generate hydrogen gas and create a porous structure.

The mixture compositions investigated in this study were developed through a multi-factor optimization program involving rice husk ash (RHA), polypropylene microfibers, polycarboxylate-based superplasticizer, and aluminum powder. The experimental mixtures presented in Table 1 were selected from the optimization program and contained different combinations of RHA and polypropylene microfiber contents within the investigated ranges. The physical and mechanical properties reported in this study correspond to the experimentally produced mixtures shown in Table 1. The objective of the study was to evaluate the performance of non-autoclaved aerated concrete (NAAC) mixtures containing rice husk ash-derived silica, polypropylene microfibers, a polycarboxylate-based superplasticizer, and aluminum powder.

The dosages of polycarboxylate superplasticizer and aluminum powder were strictly fixed at 0.40% and 0.10% by weight of cementitious materials, respectively, for all modified mixtures.

The water-to-solid ratio ranged from 0.45 to 0.55 depending on workability requirements.

Table 1. Mix compositions and averaged properties ($n = 3$).

Mix	RHA (%)	Fiber (%)	SP (%)	Al Powder (%)	Density (kg/m ³)	Strength (MPa)	Thermal (W/m·K)	Water Absorption (%)	Std (Density/Strength)
Control	0.0	0.0	0.40	0.10	580	3.75	0.135	22.2	3.87/0.06
M1	5.0	0.10	0.40	0.10	560.0	4.50	0.130	18.0	4.57/0.02
M2	5.5	0.12	0.40	0.10	550.0	4.60	0.128	17.0	4.49/0.03
M3	6.0	0.15	0.40	0.10	540.0	4.70	0.125	16.5	4.41/0.03
M4	6.5	0.18	0.40	0.10	530.0	4.75	0.123	15.5	4.33/0.03
M5	7.0	0.20	0.40	0.10	520.0	4.80	0.120	15.0	4.25/0.03

A multi-factor optimization study was performed involving RHA, polypropylene fibers, superplasticizer, and aluminum powder.

The preparation of NAAC was carried out using a controlled technological process ensuring uniform distribution of components and formation of a stable porous structure.

Initially, all dry components, including cement, ground sand, lime, gypsum, and rice husk ash, were introduced into a forced-action mixer and mixed for 2–3 min until a homogeneous dry blend was obtained.

Subsequently, the required amount of water and superplasticizer was added to the mixture. The mixing process was continued for 3–5 min to obtain a uniform slurry with adequate workability.

Polypropylene microfibers were then gradually introduced into the mixture to ensure their uniform dispersion and to prevent agglomeration.

After achieving a homogeneous mixture, aluminum powder was added in the form of a pre-prepared aqueous suspension. The mixture was then mixed for an additional 30–60 s. During this stage, the aluminum reacted with calcium hydroxide formed from cement and lime hydration, resulting in the release of hydrogen gas and initiation of pore formation.

The fresh mixture was immediately poured into molds, filling approximately 60–70% of their volume to allow for expansion. The gas formation and expansion process occurred within 15–30 min, leading to the development of a cellular structure.

Following expansion, the specimens were kept in molds under controlled conditions at a temperature of 20–40 °C and relative humidity of 60–70% for 6–8 h to achieve initial setting and sufficient green strength.

After demolding, the specimens were cured under natural conditions for 24–48 h without autoclave treatment.

Figure 1 illustrates the technological scheme used for the preparation of non-autoclaved aerated concrete (NAAC). The process includes preparation of raw materials, dry mixing of cementitious components, addition of water and superplasticizer, incorporation of polypropylene microfibers and aluminum powder suspension, casting into molds, gas formation and expansion, pre-curing, demolding, and final curing under non-autoclave conditions. The proposed technological process ensures uniform pore formation, improved mixture homogeneity, and enhanced physical and mechanical properties of the developed aerated concrete.



Figure 1. Technological scheme for the preparation of non-autoclaved aerated concrete incorporating rice husk ash-derived silica and polypropylene microfibers.

The physical and mechanical properties of the developed NAAC were evaluated using standardized test methods.

The bulk density of hardened specimens was determined according to ASTM C138 [30] by measuring mass and volume of the samples.

Compressive strength was measured using a universal testing machine in accordance with ASTM C109. Cube specimens were tested at specified curing ages, and the average value of at least three samples was reported.

XRD analysis was performed using a DRON-3 diffractometer (Bourestnik Inc., Saint Petersburg, Russia) with $\text{CuK}\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$) in the 2θ range of $5\text{--}70^\circ$ at a scanning rate of $2^\circ/\text{min}$.

TG–DTA analysis was carried out using a Q-1500D derivatograph (MOM, Budapest, Hungary) under air atmosphere at a heating rate of $10^\circ\text{C}/\text{min}$ in the temperature range of $20\text{--}1000^\circ\text{C}$.

Microstructural observations were performed using an optical microscope at $\times 5$ magnification on fractured surfaces of hardened NAAC specimens after 28 days of curing.

Thermal conductivity was determined using a steady-state method in accordance with ISO 8302 [31]. This method allows accurate measurement of heat flow through porous materials.

Water absorption was evaluated following ASTM C642 [32]. Specimens were dried to constant mass, immersed in water, and the percentage increase in mass was calculated.

Freeze–Thaw Resistance Testing The freeze–thaw resistance of the non-autoclaved aerated concrete specimens was evaluated after 28 days of standard curing in strict accordance

with GOST 10060.0–2012 [33]. Prior to testing, the cubic specimens ($100 \times 100 \times 100$ mm) were fully saturated with water at a temperature of 20 ± 2 °C. The experimental procedure involved alternating cycles of freezing in air at -18 ± 2 °C for at least 4 h, followed by thawing in water at $+20 \pm 22$ °C for at least 2 h. The mass loss and compressive strength reduction were systematically measured after specified intervals of cycles. The freeze–thaw resistance grade (F) was determined based on the maximum number of cycles completed without exceeding a 5% loss in mass and a 25% reduction in compressive strength, alongside the total absence of visible structural defects or surface cracking.

Additionally, the pore structure and uniformity were assessed qualitatively through visual inspection of fractured surfaces.

To ensure the reliability of the results, all experiments were conducted in triplicate, and the average values were reported. Standard deviations were calculated to assess the variability of the results. All testing procedures were carried out under controlled laboratory conditions.

Statistical analysis was performed using one-way analysis of variance (ANOVA) to evaluate the statistical significance of differences in compressive strength between the investigated mixture compositions. Differences were considered statistically significant at $p < 0.05$.

3. Results

3.1. Density of Non-Autoclaved Aerated Concrete

The experimental results show that the developed non-autoclaved aerated concrete (NAAC) exhibits a relatively low density in the range of 520–560 kg/m³, depending on the mixture composition.

The reduction in density compared to conventional systems is primarily attributed to the effective gas formation process induced by aluminum powder and the stabilization of the pore structure. This effect may be associated with differences in pore formation and stabilization among the investigated mixtures.

In addition, the use of a polycarboxylate-based superplasticizer enhances the flowability of the mixture, allowing for better expansion and preventing pore collapse during the early stages of hardening. As a result, a more homogeneous and finely distributed pore system is achieved.

Figure 2 illustrates the density of the optimized NAAC mixtures. The density decreased from 560 to 520 kg/m³ across the investigated compositions.

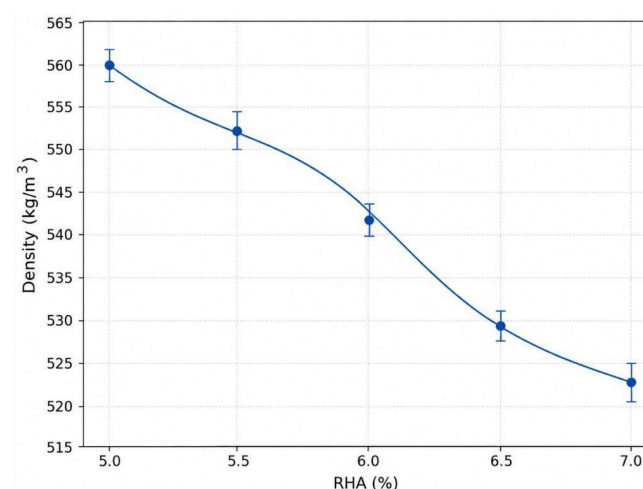


Figure 2. Density of optimized NAAC mixtures of developed NAAC compositions.

3.2. Compressive Strength

The compressive strength of the developed NAAC ranged from 4.5 to 4.8 MPa. Compared with the control composition (3.75 MPa), the modified compositions exhibited compressive strengths approximately 20–28% higher than the control mixture.

The statistical significance of the differences in compressive strength between the investigated mixtures was evaluated using one-way analysis of variance (ANOVA), and the results are presented in Table 2.

Table 2. Results of one-way ANOVA for compressive strength.

Source of Variation	df	F-Value	p-Value
Between Groups	4	66.76	3.57×10^{-7}
Within Groups	10	—	—

Figure 3 presents the compressive strength of the optimized NAAC mixtures. The investigated compositions exhibited compressive strengths ranging from 4.50 to 4.80 MPa. The observed improvement in strength may be associated with the formation of additional calcium silicate hydrate (C–S–H) due to pozzolanic reactions between amorphous silica from rice husk ash and calcium hydroxide generated during cement hydration.

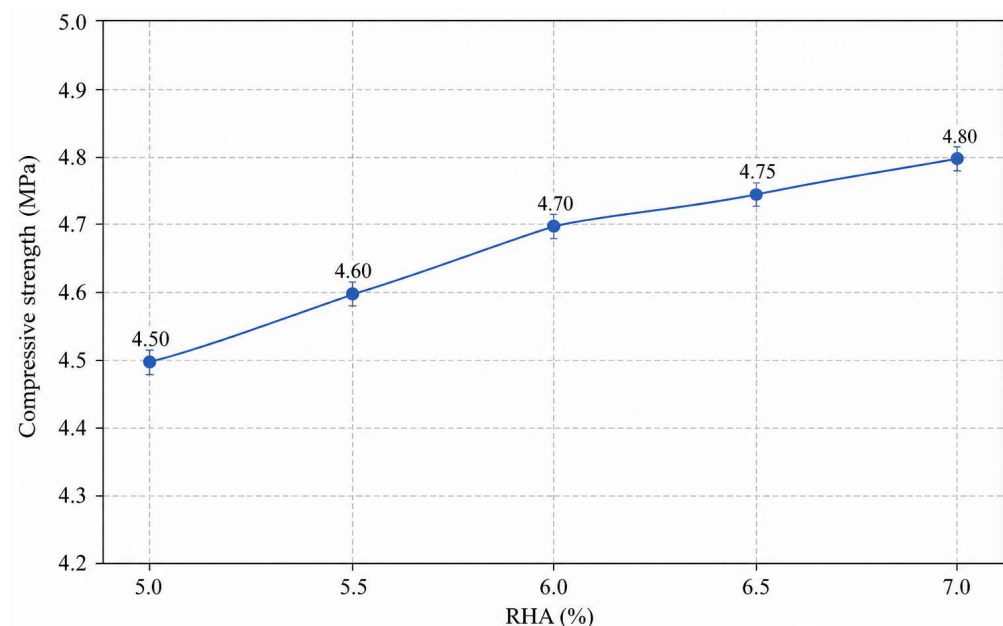


Figure 3. Compressive strength of optimized NAAC of developed NAAC compositions. Error bars indicate ± 1 standard deviation ($n = 3$).

The observed strength enhancement is consistent with previous studies indicating that finely ground RHA contributes to both pozzolanic and microfiller effects. Improved particle packing and reduced pore volume have been identified as important factors governing the mechanical performance of RHA-modified cementitious composites.

To evaluate the statistical significance of the observed strength improvement, a one-way analysis of variance (ANOVA) was performed. The ANOVA results demonstrated statistically significant differences in compressive strength among the investigated mixture compositions. Therefore, the observed differences in compressive strength among the investigated mixture compositions cannot be attributed to random experimental variability.

Comparison with Previously Reported Lightweight Aerated Concrete Systems

Table 3 compares the performance of the developed non-autoclaved aerated concrete with representative lightweight aerated concrete systems reported in the literature. At comparable densities of 520–560 kg/m³, the developed NAAC achieved compressive strengths of 4.5–4.8 MPa, which are higher than or comparable to most conventional non-autoclaved aerated concretes and foamed concretes reported previously. Furthermore, the water absorption values (15–18%) were lower than those reported for similar lightweight cementitious materials, which may be associated with improved pore refinement and matrix densification. The thermal conductivity remained low (0.120–0.130 W/m·K), suggesting the suitability of the developed material for energy-efficient building applications. The superior performance of the developed NAAC compared with most previously reported lightweight aerated concretes may be associated with the combined incorporation of rice husk ash-derived silica, polypropylene microfibers, and polycarboxylate superplasticizer, which contributed to matrix densification and improved pore structure.

Table 3. Comparison of the developed NAAC with previously reported lightweight aerated concrete systems.

Reference	Material	Density (kg/m ³)	Compressive Strength (MPa)	Water Absorption (%)	Thermal Conductivity (W/m·K)
Narayanan and Ramamurthy [1]	Conventional non-autoclaved aerated concrete	550–650	2.0–3.5	20–30	0.14–0.18
Jones and McCarthy [2]	Lightweight foamed concrete	500–700	2.0–4.5	18–28	0.13–0.18
Kearsley and Wainwright [5]	Foamed concrete	500–600	2.0–4.0	20–30	0.12–0.18
Hilal et al. [4]	Non-autoclaved foamed concrete	500–600	2.5–4.0	18–25	0.12–0.16
Amran et al. [3]	Aerated lightweight concrete	500–600	3.0–4.5	16–24	0.11–0.15
Present study	NAAC containing RHA-derived silica, polypropylene microfibers and polycarboxylate superplasticizer	520–560	4.5–4.8	15–18	0.120–0.130

The observed improvement may be explained by the combined action of several mechanisms. First, the highly reactive amorphous silica from RHA participated in pozzolanic reactions and consumed calcium hydroxide released during cement hydration. Second, the fine RHA particles acted as microfillers, improving particle packing and reducing pore wall discontinuities. Third, the polycarboxylate superplasticizer improved dispersion of solid particles and contributed to a more uniform pore structure. The combined influence of these factors resulted in improved compressive strength and reduced water absorption while maintaining low density.

3.3. XRD Analysis

To investigate the phase composition of the developed non-autoclaved aerated concrete (NAAC), X-ray diffraction (XRD) analysis was performed. The obtained diffraction pattern is presented in Figure 4.

To facilitate the interpretation of the XRD results, the chemical composition of the rice husk ash (RHA) used in this study is presented in Table 4. As shown in Table 4, the RHA contained 92.5 wt.% SiO₂ and exhibited a low loss on ignition (1.17 wt.%), indicating a high content of reactive silica and significant pozzolanic potential. These characteristics may support the formation of additional hydration products through reactions between amorphous silica and calcium hydroxide generated during cement hydration.

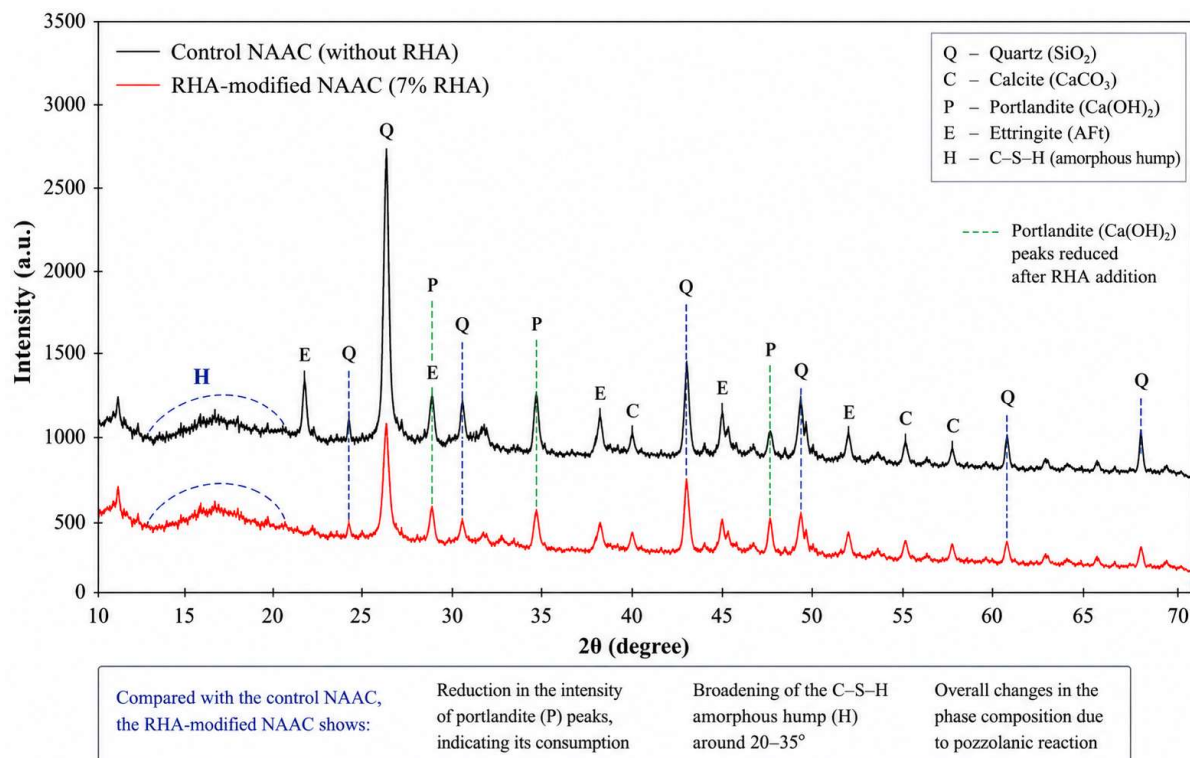


Figure 4. XRD patterns of the control NAAC and modified NAAC containing 7% rice husk ash (RHA) and polypropylene microfibers. The blue dashed curves highlight the broad amorphous C–S–H hump. Q—quartz (SiO_2), C—calcite (CaCO_3), P—portlandite [$\text{Ca}(\text{OH})_2$], E—ettringite (Aft), and H—amorphous C–S–H hump.

Table 4. Chemical composition of rice husk ash (RHA) used in the study.

Names of Oxides	RHA from “Leader” Variety (%)
SiO_2	92.5
Al_2O_3	1.45
Fe_2O_3	0.47
CaO	1.30
MgO	0.57
K_2O	1.80
Na_2O	0.54
TiO_2	-
P_2O_5	0.1
CuO	0.1
MnO	-
SO_3	-
Loss on ignition (LOI)	1.17
Total	100

Note: “-” indicates that the component was not detected.

The high silica content is comparable to values reported in the literature for highly reactive rice husk ash. Habeeb and Mahmud [6] reported an SiO_2 content of 88.32 wt.% and suggested the predominantly amorphous nature of the ash by XRD analysis.

The investigated aerated concrete composition differs from the reference system by the incorporation of rice husk ash-derived silica and polypropylene microfibers. The results of XRD analysis revealed the presence of diffraction peaks corresponding to quartz, portlandite, feldspar, and calcite phases.

The dominant diffraction maxima observed at $d = 3.34 \text{ \AA}$ and $d = 4.25 \text{ \AA}$ correspond to quartz (SiO_2), indicating the presence of crystalline siliceous phases originating from sand and rice husk ash-derived silica. The diffraction peaks at $d = 3.34 \text{ \AA}$ and $d = 4.25 \text{ \AA}$ confirm the presence of crystalline quartz phases originating from quartz sand and rice husk ash-derived silica.

Additional diffraction maxima at $d = 3.24 \text{ \AA}$ and $d = 3.18 \text{ \AA}$ correspond to potassium feldspar and feldspar phases, respectively. The diffraction peak at $d = 3.03 \text{ \AA}$ is associated with calcite formation, while peaks at $d = 4.90 \text{ \AA}$, $2.63 \text{ \AA}$, and $1.927 \text{ \AA}$ correspond to portlandite (Ca(OH)_2), which is formed during cement hydration.

The high silica content of the RHA used in this study is consistent with previous investigations. Nehdi et al. reported that properly processed rice husk ash contains highly reactive silica and exhibits significant pozzolanic activity. XRD analysis confirmed the predominantly amorphous nature of the ash, which contributes to its ability to participate in secondary hydration reactions.

The formation of such phases suggests the occurrence of pozzolanic reactions and the gradual conversion of calcium hydroxide into additional cementitious products.

The modified NAAC specimen exhibited reduced portlandite peak intensity and a more pronounced amorphous hump, suggesting enhanced hydration and pozzolanic reactions.

Figure 4 compares the XRD patterns of the control NAAC and the modified NAAC incorporating 7% RHA and polypropylene microfibers. Both compositions exhibited diffraction peaks corresponding to quartz, portlandite, calcite, and ettringite phases. Compared with the control specimen, the modified NAAC showed lower portlandite peak intensity and a broader amorphous C–S–H hump, which is consistent with the pozzolanic reaction of RHA and the formation of additional hydration products.

The observed changes in phase composition are mainly attributed to the incorporation of RHA-derived silica, whereas polypropylene microfibers did not introduce new crystalline phases and were not directly detectable by XRD.

The dominant diffraction peaks corresponding to quartz (Q) were identified in both the control and modified NAAC specimens, indicating the presence of crystalline silica originating from quartz sand and rice husk ash-derived silica.

Additional diffraction maxima attributable to feldspar phases were identified. Portlandite peaks indicate the formation of calcium hydroxide during cement hydration, which subsequently participates in pozzolanic reactions with amorphous silica from rice husk ash. Calcite (C) peaks are associated with partial carbonation of hydration products.

Weak and broad diffraction features may be associated with poorly crystalline calcium silicate hydrate (C–S–H) phases formed during hydration and pozzolanic reactions. These phases contribute to densification of the cementitious matrix and improvement in the mechanical performance of the developed NAAC compositions.

The broad background region and weakly crystalline C–S–H phase indicate the formation of an amorphous hydration structure typical for non-autoclaved aerated concrete systems. The obtained XRD results suggest that the incorporation of rice husk ash-derived silica promotes additional hydration reactions and enhances the microstructural development of the developed NAAC compositions.

3.4. Pore Morphology and Microstructural Characteristics of Interpore Walls

The physical, mechanical, and thermal performance indicators of non-autoclaved aerated concrete (NAAC)—specifically compressive strength, dry density, and thermal conductivity—are fundamentally governed by its structural architecture. This architecture comprises two interdependent levels: the macro-level pore morphology (pore size distribution, volume, and alignment) and the micro-level density of the solid interpore walls.

To evaluate these structural features and clarify the performance trajectories reported in Table 1, optical microscopy and microstructural analyses were conducted after 28 days of standard curing.

Optical micrographs evaluating the evolution of the cellular structure are presented in Figure 5. The control NAAC composition (Figure 5a) exhibited a highly heterogeneous and unstable pore network. It is characterized by irregularly shaped, non-spherical voids and a high degree of bubble coalescence. Such coalescence typically occurs during the gas-formation phase due to insufficient yield stress of the initial cement slurry, resulting in localized structural discontinuities and large interconnected voids that may adversely affect the mechanical performance of the material.

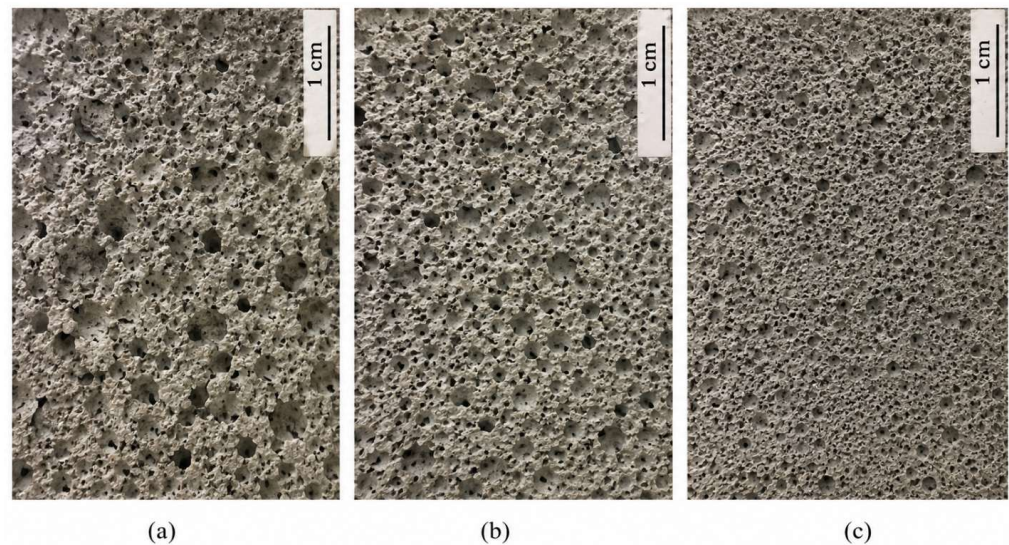


Figure 5. Optical micrographs ($\times 50$) showing the cellular matrix and inter pore wall structure of non-autoclaved aerated concrete after 28 days of curing: (a) control NAAC; (b) NAAC incorporating rice husk ash (RHA); and (c) NAAC incorporating RHA, polypropylene microfibers, and polycarboxylate superplasticizer.

The individual incorporation of rice husk ash-derived amorphous silica (Figure 5b) visibly altered the cellular structure. The pore system became more uniformly distributed, with a clear reduction in the occurrence of large, irregular voids, while the inter pore walls appeared more continuous and compact. This structural modification may be associated with the filler effect and pozzolanic activity of finely dispersed RHA. Acting as a reactive pozzolanic agent, the amorphous silica particles consume free calcium hydroxide (portlandite, $\text{Ca}(\text{OH})_2$) generated during cement hydration, converting it into supplementary, poorly crystalline calcium silicate hydrate (C–S–H) phases. This secondary C–S–H gel effectively blocks capillary channels and micro-defects within the solid matrices forming the pore walls, thereby increasing their density and continuity.

For the modified composition incorporating both RHA and polypropylene microfibers under optimized polycarboxylate superplasticizer content (Figure 5c), the microstructure demonstrated the highest degree of uniformity and spatial consistency. The pores appeared more regular and uniformly distributed throughout the matrix, while fewer visible structural defects were observed. This behavior may be associated with improved mixture homogeneity provided by the polycarboxylate superplasticizer and the incorporation of rice husk ash-derived silica.

However, quantitative pore structure characterization (average pore size, pore size distribution, and total porosity) was beyond the scope of the present study and will be considered in future investigations.

The obtained microstructural observations are in agreement with the XRD and TG–DTA results and qualitatively suggest improved structural homogeneity and pore distribution in the modified NAAC compositions. Optical micrographs evaluating the evolution of the cellular structure are presented in Figure 5.

3.5. TG–DTA Analysis

TG–DTA analysis was performed to evaluate the thermal behavior and hydration products of the developed non-autoclaved aerated concrete compositions. Thermal analysis alone does not provide complete information about the phase composition of cementitious systems, since some phases may remain thermally inactive within the investigated temperature range. Therefore, TG–DTA results were interpreted together with XRD and microstructural observations.

The obtained thermograms revealed several characteristic thermal effects associated with dehydration and phase transformations of hydration products. Endothermic effects observed in the temperature range of 80–140 °C are associated with the removal of physically bound water and dehydration of calcium silicate hydrate (C–S–H) phases.

A pronounced endothermic effect near 420–450 °C corresponds to the decomposition of portlandite $\text{Ca}(\text{OH})_2$. The reduction in intensity of this effect in RHA-modified compositions suggests the occurrence of pozzolanic reactions and possible additional C–S–H formation.

The thermal effects detected in the range of 600–650 °C may be associated with dehydration of calcium hydrosilicates and transformation of partially crystallized C–S–H phases. Endothermic effects near 700–800 °C are related to decarbonation of calcium carbonate, while the exothermic effect observed near 800 °C can be attributed to recrystallization processes and transformation of hydration products into wollastonite-type phases.

The obtained TG–DTA results are in agreement with the XRD and microstructural analysis, suggesting that the incorporation of rice husk ash-derived amorphous silica may promote enhanced hydration reactions.

The TG–DTA curves of the control non-autoclaved aerated concrete are presented in Figure 6.

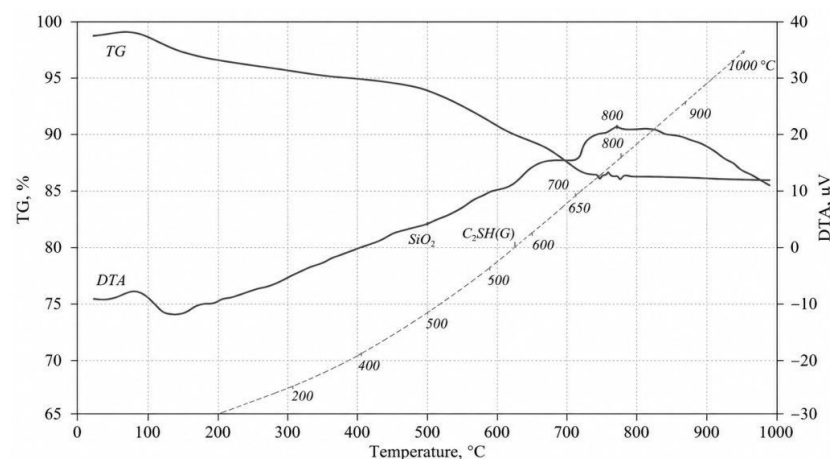


Figure 6. TG–DTA curves of control non-autoclaved aerated concrete (NAAC).

The TG–DTA analysis revealed endothermic effects in the temperature range of 80–140 °C associated with dehydration of physically bound water and calcium silicate hydrate phases. The endothermic peak observed near 420–450 °C corresponds to the decomposition of portlandite $\text{Ca}(\text{OH})_2$, while the thermal effects detected at 700–800 °C are associated with decarbonation of calcium carbonate and transformation of hydration prod-

ucts. The reduction in portlandite-related peaks in RHA-modified compositions suggests the occurrence of pozzolanic reactions and additional formation of C–S–H phases.

The increased $\text{Ca}(\text{OH})_2$ content and reduced amount of residual quartz and feldspar may suggest enhanced hydration reactions and a more efficient utilization of reactive silica in the cementitious matrix.

This is suggested by the TG–DTA results: the area of thermal effects associated with C–S–H phases near 800 °C and tobermorite (200–220 °C) increases. The mass loss during heating was higher for the composition containing RHA, polypropylene microfibers, and polycarboxylate-based superplasticizer (20%) compared to the composition containing only RHA (17.6%). This behavior may indicate a more complete course of hydration reactions in finely ground mixtures. The TG–DTA curves of the modified NAAC containing RHA, polypropylene microfibers, and polycarboxylate-based superplasticizer are presented in Figure 7.

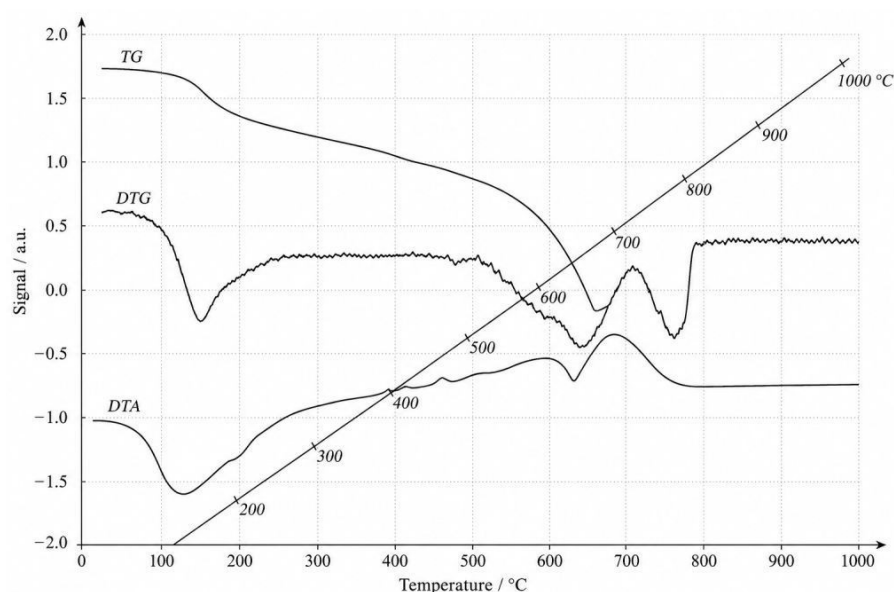


Figure 7. TG–DTA curves of NAAC containing rice husk ash (RHA), polypropylene microfibers, and polycarboxylate-based superplasticizer.

According to XRD patterns and TG–DTA curves, calcium carbonate was identified in all NAAC samples by diffraction lines at 3.03, 2.28, 1.91, and 1.87 Å and by an endothermic effect in the range of 700–800 °C.

In thermograms of finely ground NAAC compositions, the endothermic effect is bifurcated based on finely ground mixtures: the first peak can be associated with decomposition of calcium carbonate formed during partial carbonation of portlandite and calcium hydrosilicates from the aerated concrete cementitious matrix, and the second peak is associated with the decomposition of calcium carbonate present in the silica component.

The obtained TG–DTA results suggest that incorporation of rice husk ash may promote additional formation of hydration products, particularly low-basic calcium silicate hydrate phases. Improved dispersion of the raw material components contributed to a more complete interaction between the cementitious and siliceous phases, resulting in reduced content of residual quartz and feldspar phases. In compositions containing RHA, polypropylene microfibers, and polycarboxylate superplasticizer, the thermal effects suggest enhanced hydration processes and stabilization of the cementitious matrix.

3.6. Thermal Conductivity

The thermal conductivity of the developed material was found to be in the range of 0.12–0.13 W/m·K, which is within the range commonly reported for lightweight aerated concrete materials.

The low thermal conductivity is mainly associated with the high porosity and the presence of uniformly distributed air voids, which reduce heat transfer through the material. The incorporation of RHA may contribute to the refinement of the pore structure, leading to smaller and more evenly distributed pores.

These characteristics suggest that the developed NAAC may be suitable for energy-efficient construction applications where thermal insulation is required.

Figure 8 shows the thermal conductivity values of the developed non-autoclaved aerated concrete compositions. The thermal conductivity decreased from 0.130 to 0.120 W/(m·K) for the investigated compositions. The reduction in thermal conductivity is mainly associated with the formation of a more uniform porous structure and improved pore refinement, which reduced heat transfer through the material.

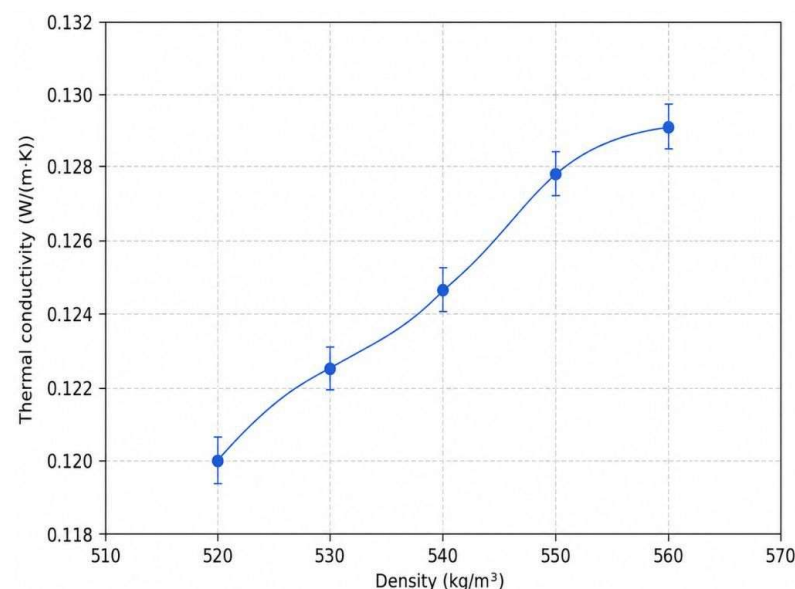


Figure 8. Thermal conductivity of developed NAAC compositions.

3.7. Water Absorption

The water absorption of the investigated compositions ranged from 15% to 18%, compared with 22.2% for the control mixture.

This improvement is mainly due to the densification of the cement matrix caused by pozzolanic reactions involving RHA. The formation of additional C–S–H reduces capillary porosity and limits water penetration.

Moreover, the improved pore structure, characterized by a higher proportion of closed pores, contributes to reduced water absorption.

Figure 9 shows that water absorption decreased from 18.0% for Mix M1 to 15.0% for Mix M5 as the RHA content increased from 5% to 7%. Compared with the control mixture (22.2%), all RHA-modified compositions exhibited water absorption values of 15–18%, compared with 22.2% for the control mixture, corresponding to a reduction of approximately 19–32%.

The observed reduction in water absorption is consistent with the improved microstructural homogeneity observed in Figure 5 and with the hydration-related changes indicated by the TG–DTA results presented in Figures 6 and 7. The modified NAAC compositions exhibited a more uniform pore distribution and fewer visible structural defects,

which contributed to reduced water penetration. The combined results of water absorption, XRD, microstructural observations, and TG–DTA analyses indicate that the incorporation of RHA improves the overall stability of the cementitious matrix.

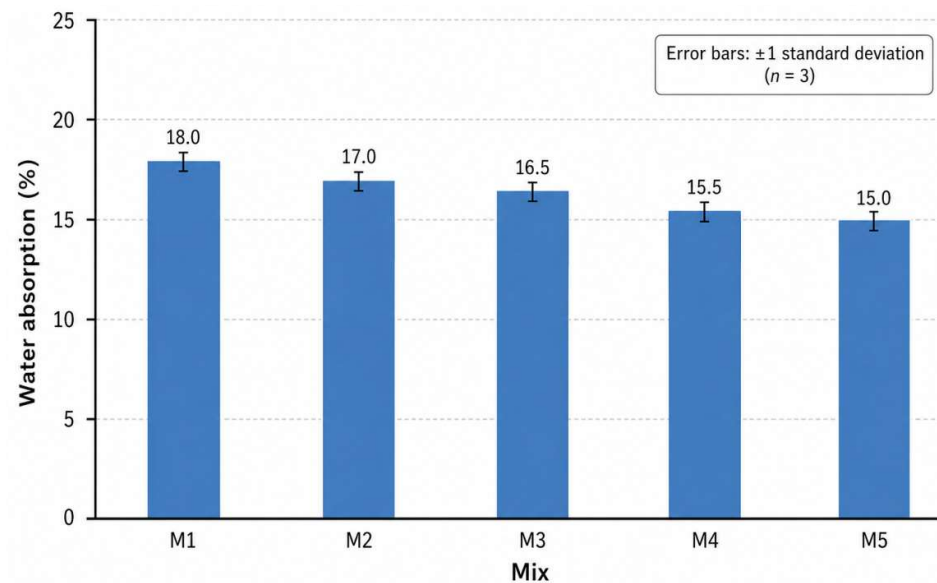


Figure 9. Water absorption of developed NAAC compositions.

3.8. Freeze–Thaw Resistance

Freeze–thaw resistance was evaluated in accordance with GOST 10060.1. The obtained results are presented in Table 5.

Table 5. Frost resistance coefficient of developed NAAC compositions.

Mix	25 Cycles	35 Cycles	50 Cycles
Control	0.85	0.82	0.75
M1	0.98	0.89	0.85
M2	0.97	0.90	0.86
M3	0.97	0.92	0.865
M4	0.98	0.94	0.87

The developed NAAC compositions demonstrated satisfactory resistance to cyclic freezing and thawing. After 50 freeze–thaw cycles, the frost-resistance coefficient ranged from 0.75 for the control composition to 0.87 for the composition containing 7% RHA. The RHA-modified compositions exhibited higher frost resistance coefficients than the control mixture, indicating improved resistance to freeze–thaw deterioration.

The improved performance may be associated with reduced water absorption and a more homogeneous pore structure, which decrease internal stresses generated during ice formation. The effect of freeze–thaw cycles on the frost resistance coefficient of the control and RHA-modified NAAC compositions is presented in Figure 10.

The frost resistance results indicate that the incorporation of rice husk ash improved the resistance of NAAC to cyclic freezing and thawing. After 50 freeze–thaw cycles, the frost resistance coefficient increased from 0.75 for the control composition to 0.87 for the modified composition. The improved frost resistance may be associated with reduced water absorption and a more homogeneous pore structure, which decrease internal stresses generated during ice formation. These results suggest that RHA-modified NAAC exhibits improved durability under freeze–thaw exposure compared with the control mixture.

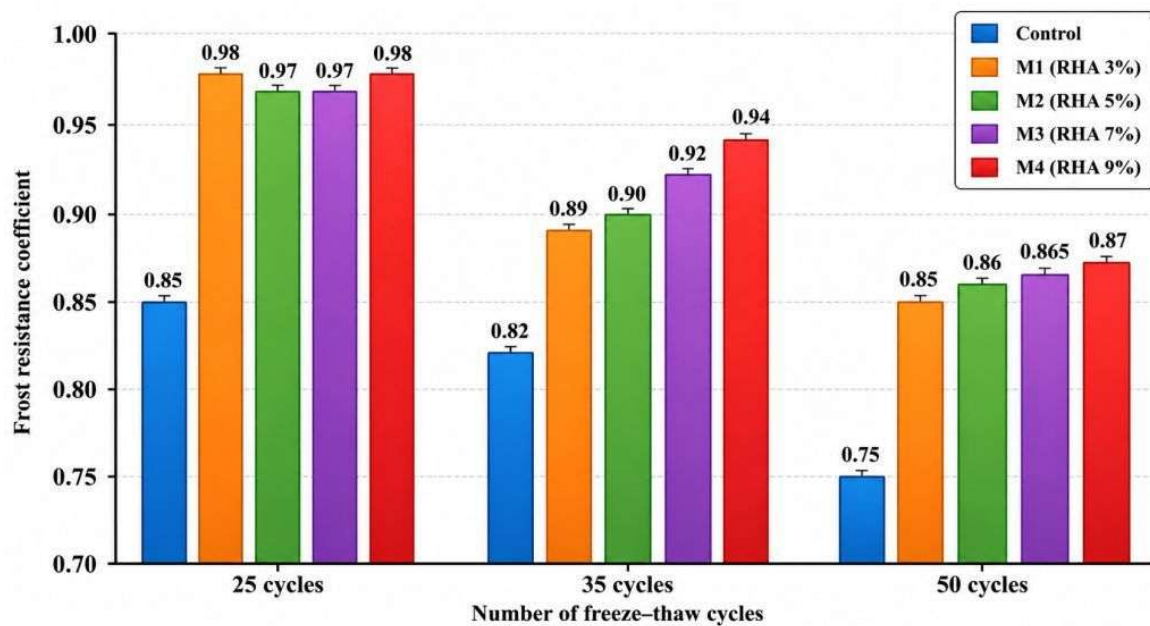


Figure 10. Effect of freeze–thaw cycles on the frost resistance coefficient of control and RHA-modified NAAC compositions.

3.9. Performance of Developed NAAC Compositions

The combined use of RHA, polypropylene fibers, and superplasticizer resulted in improved physical and mechanical properties of NAAC.

- RHA contributed to matrix densification and strength development
- Superplasticizer enhanced mixture homogeneity and pore stability
- Polypropylene microfibers were associated with improved structural homogeneity and pore distribution

As a result, the developed NAAC exhibited a balanced combination of:

- low density
- high compressive strength
- reduced water absorption and improved freeze–thaw resistance
- enhanced thermal insulation performance

3.10. Summary of Results

The main experimental findings can be summarized as follows:

Density: 520–560 kg/m³

Compressive strength: 4.5–4.8 MPa

Thermal conductivity: 0.12–0.13 W/m·K

Water absorption: 15–18%

These results demonstrate that the proposed composition significantly outperforms conventional non-autoclaved aerated concrete in terms of both mechanical and physical properties.

4. Discussion

The obtained results demonstrate that the developed non-autoclaved aerated concrete (NAAC) incorporating rice husk ash (RHA) and polypropylene fibers exhibits a significant improvement in mechanical and physical properties compared to conventional compositions.

The observed improvement can be explained by the combined action of three mechanisms. First, the highly reactive amorphous silica from RHA participated in pozzolanic

reactions and consumed calcium hydroxide released during cement hydration. Second, the fine RHA particles acted as microfillers, improving particle packing and reducing pore wall discontinuities. Third, the polycarboxylate superplasticizer improved dispersion of solid particles and contributed to a more uniform pore structure. The combined influence of these factors resulted in improved compressive strength and reduced water absorption while maintaining low density.

The improvement in compressive strength observed in the present study can be explained by the pozzolanic activity of rice husk ash (RHA). The high amorphous silica content of the RHA (92.5 wt.% SiO₂) promoted reactions with calcium hydroxide released during cement hydration, resulting in the formation of additional hydration products. This interpretation is supported by the reduced intensity of portlandite peaks observed in the XRD patterns and by the corresponding thermal effects identified in the TG-DTA analysis. These changes contributed to the development of a more homogeneous cementitious matrix and improved mechanical performance.

In addition to the chemical contribution of RHA, the observed improvement in performance was associated with modifications of the pore structure. Optical microscopy revealed a more uniform pore distribution and fewer visible structural defects in RHA-modified compositions. These microstructural features are consistent with the measured increase in compressive strength and reduction in water absorption. Similar trends have been reported in previous studies on RHA-modified lightweight cementitious materials, where improved hydration and pore structure development contributed to enhanced engineering performance.

The reduction in water absorption observed in the present study is consistent with previous findings reported by Nehdi et al. The authors demonstrated that highly reactive rice husk ash can significantly reduce the permeability of cementitious materials due to its pozzolanic activity and its influence on pore structure development. These mechanisms are generally associated with improved durability-related properties.

The increase in compressive strength (up to 4.8 MPa) can be primarily attributed to the pozzolanic activity of rice husk ash. As reported by Habeeb and Mahmud [6], RHA contains a high amount of amorphous silica, which reacts with calcium hydroxide formed during cement hydration. This reaction leads to the formation of additional calcium silicate hydrate (C-S-H), which enhances the density and integrity of the cementitious matrix.

The improvement in compressive strength can be attributed not only to the pozzolanic reactivity of RHA but also to its physical filler effect. Similar observations were reported by Bui et al. [8], who demonstrated that finely ground RHA improves particle packing, reduces porosity, and decreases particle spacing within the cementitious matrix. These mechanisms contribute to enhanced strength development in addition to the chemical consumption of calcium hydroxide during pozzolanic reactions.

Similar findings were reported by Givi et al. [11], who observed that RHA increases compressive strength from 3.75 to 4.80 MPa (28%) the mechanical performance of cement-based composites due to microstructural densification. In the present study, the incorporation of 5–7% RHA resulted in a noticeable increase in strength compared to reference mixtures without silica additives.

Furthermore, the reduction in water absorption (to 15–18%) indicates a refinement of the pore structure. This observation is consistent with the results of Chindaprasirt et al. [12], who demonstrated that RHA reduces capillary porosity and improves durability characteristics.

Moreover, Banthia and Gupta [18] reported that fiber reinforcement enhances toughness and impact resistance, which is particularly important for brittle materials such as aerated concrete. The formation of a uniform pore structure is a key factor influencing the per-

formance of aerated concrete. In this study, aluminum powder was used as a gas-forming agent, producing hydrogen gas through chemical interaction with calcium hydroxide.

According to Alhozaimy et al. [19], polypropylene fibers may improve the post-cracking behavior of cementitious materials. However, crack resistance and shrinkage behavior were not directly evaluated in the present study. Therefore, the role of polypropylene microfibers is discussed only in terms of their association with improved structural homogeneity and pore distribution.

The resulting density (520–560 kg/m³) indicates successful pore formation and stabilization. According to Narayanan and Ramamurthy [1], the uniformity of pore distribution plays a decisive role in achieving an optimal balance between strength and density.

The improved thermal conductivity (0.12–0.13 W/m·K) can also be attributed to the uniform pore structure. As reported by Kearsley [24], smaller and evenly distributed pores reduce heat transfer, thereby enhancing insulation properties.

The use of a polycarboxylate-based superplasticizer contributed to improved workability and reduced water demand. This resulted in a lower water-to-solid ratio, which is known to enhance mechanical strength.

Plank and Hirsch [26] demonstrated that polycarboxylate superplasticizers improve dispersion of cement particles, leading to more homogeneous mixtures. In the present study, this effect contributed to better pore stability and reduced segregation during gas formation.

Additionally, Collepardi [28] reported that modern superplasticizers enhance the rheological behavior of cementitious systems, which is essential for producing high-quality aerated concrete.

One of the key findings of this study is the beneficial combined effect of RHA, polypropylene fibers, and superplasticizer on the performance of NAAC.

RHA → improves microstructure and strength

Superplasticizer → stabilizes mixture and pore structure

This combined effect leads to superior performance compared to systems where these components are used individually.

Previous studies have mostly investigated these materials separately. For example, Van Tuan et al. [16] focused on RHA in high-performance concrete, while Li [20] studied fiber-reinforced composites. However, their combined application in NAAC systems has not been sufficiently explored.

The present study demonstrates that integrating these components results in:

- improved mechanical strength
- reduced density
- enhanced durability
- better thermal performance

Compared to traditional NAAC systems reported in the literature, the developed material shows clear advantages.

Amran et al. [3] reported compressive strength values typically below 3 MPa for non-autoclaved systems. In contrast, the present study achieved values up to 4.8 MPa, indicating a substantial improvement.

Similarly, the density achieved in this study is lower than many conventional systems, while maintaining higher strength. This combination of properties is particularly desirable for structural and insulation applications.

The results of this study have important practical implications:

- utilization of agricultural waste (rice husk ash)
- reduction in environmental impact
- improved performance of non-autoclaved aerated concrete
- potential for local raw material use (dune sand)

These advantages make the proposed material a promising candidate for sustainable construction.

Compared with conventional non-autoclaved aerated concrete reported in the literature, the developed compositions achieved compressive strength values of 4.5–4.8 MPa at densities of 520–560 kg/m³ and water absorption values of 15–18%. These results indicate that the developed NAAC provides a favorable balance between low density, mechanical performance, and thermal insulation. The obtained performance is comparable to or higher than that reported for many lightweight non-autoclaved aerated concrete systems incorporating supplementary cementitious materials.

5. Conclusions

This study presents the development and investigation of a non-autoclaved aerated concrete (NAAC) incorporating rice husk ash (RHA), polypropylene microfibers, and a polycarboxylate-based superplasticizer. Based on the experimental results and analysis, the following conclusions can be drawn:

The proposed NAAC composition demonstrates a significant improvement in performance, achieving a compressive strength of 4.5–4.8 MPa at a relatively low density of 520–560 kg/m³, which exceeds the typical values reported for conventional non-autoclaved aerated concrete systems.

The incorporation of rice husk ash (5–7%) enhances the mechanical properties due to its high pozzolanic activity, leading to the formation of additional calcium silicate hydrate (C–S–H) and resulting in a denser and more homogeneous microstructure.

The incorporation of polypropylene microfibers, scaled from 0.10% to 0.20% as shown in Table 1, was associated with improved structural homogeneity and pore distribution within the non-autoclaved aerated concrete matrix.

The use of a polycarboxylate-based superplasticizer was associated with improved mixture homogeneity and pore stability in the developed NAAC compositions.

XRD, microstructural, and TG–DTA analyses suggested that incorporation of rice husk ash-derived amorphous silica promotes additional formation of low-basic calcium silicate hydrate (C–S–H) phases, refinement of the pore structure, and densification of the cementitious matrix. The thermal analysis revealed reduced portlandite-related effects and enhanced pozzolanic interaction in modified NAAC compositions.

The developed material exhibits improved durability-related properties, including reduced water absorption (15–18%) and lower thermal conductivity (0.12–0.13 W/m·K), which makes it suitable for energy-efficient building applications.

The present study focused primarily on the density, compressive strength, thermal conductivity, water absorption, and microstructural characteristics of the developed non-autoclaved aerated concrete. Although the obtained results demonstrate promising engineering performance, several important durability-related properties, including drying shrinkage, sulfate resistance, carbonation resistance, and chloride penetration resistance, were not investigated. Therefore, further studies are required to comprehensively evaluate the long-term durability and service performance of the developed material under various environmental conditions.

The conclusions of the present study are limited to the investigated mixture compositions and experimental conditions. Because several mixture components were varied simultaneously during the optimization program, the individual contribution of rice husk ash, polypropylene microfibers, superplasticizer, and aluminum powder cannot be quantified independently. Future studies employing dedicated factorial experimental designs are recommended to clarify the specific influence of each component on the physical, mechanical, and durability properties of non-autoclaved aerated concrete.

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