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Physical–Mechanical and Microstructural Properties of Non-Autoclaved Aerated Concrete with Ash-and-Slag Additives

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Abstract: Non-autoclaved aerated concrete (NAAC) is gaining attention for its strength-to-weight ratio and sustainability benefits. Produced by incorporating a blowing agent into a binder, aggregate, and water mixture, NAAC offers a lightweight and porous construction material. Ash and slag waste (ASW), primarily composed of silicon, aluminum, iron, and calcium oxides, presents significant potential as a sustainable additive. However, industrial-scale processing of ASW still needs to be explored in Kazakhstan. This study evaluates the feasibility of utilizing ASW from the Ust-Kamenogorsk Thermal Power Plant to produce earthquake-resistant NAAC. Incorporating 31.5% ASW by weight optimizes compressive strength, achieving 2.35 MPa and significantly improving the mechanical properties. Chemical and microstructural analyses confirm ASW's suitability as a construction material. The study also introduces innovative processing methods and explores convolutional neural network models for predicting material structure changes, providing insights into optimizing production processes. The findings address the research objectives by confirming the viability of ASW in NAAC production and demonstrating its potential for sustainable construction. The results offer a pathway for industrial-scale applications, contributing to waste utilization and resource conservation.

Keywords: non-autoclaved aerated concrete; ash-and-slag waste; sustainable construction; microstructure analysis; artificial intelligence

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1. Introduction

Kazakhstan's energy resources, a significant player on the global stage, are primarily composed of coal (46%) and uranium (29%), with oil and gas contributing less than 25%. The country ranks among the top 20 global producers of primary energy, generating around 157 million tons of oil equivalent annually. Coal is the primary fuel for Kazakhstan's thermal power plants, producing 85% of its electricity. It is widely available, affordable, and versatile, though its quality is relatively low due to high moisture, ash, and sulfur content. Most reserves are concentrated in central Kazakhstan, including major basins like Karaganda, Ekibastuz, and Maykubensk [1–3].

Over 80% of the coal burned in thermal power plants has a high ash content (40–50%), leading to significant environmental challenges. These include air pollution caused by ash, carbon, nitrogen oxides, and slagging of heating surfaces. Such emissions contribute to a higher environmental impact in Kazakhstan than many other regions. Addressing these challenges, particularly the efficient utilization of coal combustion by-products such as ASW, presents an opportunity for sustainable development in the construction sector. The potential for integrating ASW into NAAC forms the core focus of this study, aiming to mitigate environmental impacts while developing cost-effective and durable construction materials, thereby ensuring the economic viability of the solution.

Aerated concrete is a widely used engineered product in construction due to its lightweight properties and favorable strength-to-weight ratio. However, despite its advantages over other alternatives, the performance of aerated concrete, particularly under in-plane and out-of-plane seismic loads, remains to be determined [4]. Previous studies have investigated the seismic performance of infill walls made of aerated concrete, demonstrating that technical solutions can effectively isolate these walls from seismic deformations induced by frame systems. These findings highlight the potential for creating seismically safe aerated concrete walls.

Autoclaved aerated concrete (AAC) is popular worldwide as an infill material due to its lightweight nature, excellent insulation, fire resistance, and high durability. In Turkey, for instance, AAC accounts for over 20% of the infill wall market. However, past earthquakes have shown that the seismic performance of infill walls has often been inadequate, resulting in both economic losses and psychological impacts. To address this, there is a growing demand for wall systems that can withstand seismic events without sustaining damage. Research indicates that structural engineers can design reinforced concrete frame buildings in compliance with modern seismic codes, allowing these systems to behave with ductility under seismic loads.

Comparative studies have demonstrated that NAAC, when manufactured using high-quality factory equipment, can match or even exceed the performance of gas silicate blocks. Moreover, NAAC production is 20–30% more cost-effective than AAC due to more straightforward and less expensive manufacturing requirements. While AAC production necessitates large-scale facilities and costly autoclaves, NAAC can be produced in smaller setups with minimal equipment, making it a more accessible and economical alternative.

NAAC has garnered significant attention for its potential in sustainable construction. This lightweight, porous material is created by introducing foaming agents into a mix of binder, aggregate, and water. Innovative applications have further enhanced its performance. For example, using recycled AAC as a partial sand replacement has increased compressive strength by up to 16%, attributed to an improved tobermorite phase and crystalline morphology, with evident environmental and economic benefits [5]. Strength development in LC3-50-based AAC has also been linked to katoite and carbonation processes, with properties varying based on block densities between 500 and 700 kg/m^3 [6].

Substituting 4–16% of cement with microsilica (MS) in NAAC has improved compressive strength, peaking at 16% MS, alongside better thermal conductivity and a more refined microstructure [7]. Furthermore, the integration of machine learning techniques, particularly neural networks, has demonstrated high accuracy in predicting NAAC properties, highlighting the potential of ash-and-slag waste as a key component for earthquake-resistant construction [8]. Similarly, using fly ash (FA) and bottom ash (BA) as partial replacements resulted in improved compressive (12.687 MPa) and tensile (1.540 MPa) strengths, reinforcing the viability of industrial waste in lightweight concrete [9].

Natural pozzolana (NP) as a cementitious replacement (5–20%) has also been shown to improve durability and mechanical properties, with 15% identified as optimal for maximizing strength [10]. Additionally, reinforcing NAAC with plant fibers, such as sisal (SF) and coconut fibers (CFs), further enhanced compressive and bending strengths by up to 40% and 47%, respectively, while reducing density and thermal conductivity [11].

Other approaches, such as replacing up to 35% of fine aggregate with fly ash cenospheres (FACs), maintained strength within target limits while improving sustainability [12]. Modified desert sand (DS) in alkali-activated cement (AAC) demonstrated optimal performance at a 10% dosage, with compressive strength reaching 72.3 MPa [13]. Fiber-reinforced AAC panels offered improved mechanical properties and impact resistance, though brittle failure modes underlined safety considerations [14].

The authors of reference [15] proposed a composition of non-autoclaved aerated concrete based on hydrotreatment ash (ash-and-slag mixture) from Tverskaya TPP-4. This ash is ash of mixed character (approximately coal ash by 60% and peat ash by 40%). In literature sources, there is little information about using this type of ash as a silica component for aerated concrete. The obtained aerated concrete is characterized by a uniform, highly porous structure, an average density of D500 grade (465 kg/m^3), and strength class B1 (1.64 MPa). The calculated economic effect of aerated concrete production based on the results of the pilot batch production was 400 rubles/m^3.

The chemical composition of ASW is conditioned by the quality of coal burnt at power sources. It is represented mainly by silicon, aluminum, iron, and calcium oxides, which account for up to 95% of the waste mass. There are three main types of ash and slag. The first type is fine dry fly ash, formed during coal combustion and captured by electrostatic precipitators. The second type is slags. They are formed in the boiler; they are larger, non-combustible vitreous mineral particles. The third is ash-and-slag material. It is a mix of fly ash, bottom ash, and water, which is delivered to ash disposal sites in the form of pulp. Ash and slag have been globally recognized as reliable and safe building materials with diverse applications. For instance, in China, legislation prohibits the extraction and use of natural mineral resources in construction within an 80 km radius of a TPP ash dump, promoting the utilization of industrial waste. As highlighted in references [16–18], the current state of energy-efficient structures made from aerated concrete demonstrates the material's potential in residential construction. The study examines key properties of aerated concrete, including its composite nature, structural strength, and thermal performance. These findings underscore the importance of optimizing material properties to enhance energy efficiency and durability in construction. The analysis of existing problems of gas concrete production in the Republic of Uzbekistan is also presented. The research results on the use of industrial waste in aerated concrete have shown the expediency of continuing research on physical–mechanical and chemical activation methods for wide application of secondary activation of filler in construction production. The current state of construction of external wall structures of energy-efficient residential buildings from aerated concrete is presented, and the main properties of aerated concrete are analyzed.

The properties of composite building materials, including strength and thermal performance, are influenced by their structure. An analysis of existing challenges in producing aerated concrete in the Republic of Uzbekistan highlights specific regional issues, providing insights into how local conditions affect material production and performance.

In Russia, as in Kazakhstan, which has significant coal-based energy industries, high-calcium ashes are actively utilized in construction materials. However, their application remains challenging due to fluctuations in composition, variable properties, and the high content of free CaO [19]. These challenges necessitate the development of robust processing and quality control methods to ensure consistent results.

Efforts to optimize the production of NAAC have focused on two primary directions: varying the composition of the initial mixture and innovating production methods and equipment. For instance, researchers [20] have proposed using the Taguchi method and ANOVA test to systematically evaluate the effects of compositional variations, offering a valuable framework for achieving optimal material properties. The results showed that Portland cement, phosphogypsum, and quicklime positively affected the compressive strength of non-autoclaved aerated concrete. The composition of lightweight concrete using 34% Portland cement, 35% phosphogypsum, and 10% quicklime to obtain a compressive strength of 20.93 kg/cm^2 with an elasticity of 806 kg/m^3 was found to be optimum. The paper [21] presents the results of experimental studies of porosity parameters, strength properties, and properties of aerated concrete based on industrial waste. The constructively optimal amount of water reflecting physical–mechanical, thermal, and technical properties of exterior wall constructions based on aerated concrete was determined. The change in the properties of aerated concrete and the wastes of quartz sand and slag from steel-smelting manufacturing is investigated. Mathematical regression methods and determining materials' physical and mechanical properties achieve optimization of aerated concrete composition. The results of research on the automation of the calculation of the proposed composition of aerated concrete and the amount of industrial waste by its grades are given. NAAC has gained significant attention as a sustainable construction material due to its lightweight properties and cost-effective production process. However, the effective use of industrial by-products, such as ASW, in NAAC production remains underexplored, particularly in Kazakhstan. While existing studies have demonstrated the potential of ASW to enhance concrete's physical and mechanical properties, limited research addresses its industrial-scale application or examines its impact on earthquake resistance.

This research aims to bridge these gaps by evaluating the feasibility of using ASW from the Ust-Kamenogorsk Thermal Power Plant in NAAC production. The study also introduces innovative methodologies for analyzing and optimizing the material's microstructure, including digital technologies and convolutional neural networks. These approaches represent a novel contribution to the field, offering both theoretical insights and practical solutions for sustainable construction. By addressing the variability in ASW composition and its effects on NAAC properties, this research advances the understanding of sustainable material development and provides a framework for industrial application.

One of the main criteria for large-scale application of ash and slag materials is their complete environmental safety. It is established that ash-and-slag material complies with national and inter-national sanitary-epidemiological norms, rules, and hygienic standards [22]. It is completely safe, non-toxic and can be used not only in construction but also in the technical stage (planning, slope formation, backfilling of excavations and pits) of reclamation of disturbed lands, elimination of consequences of subsoil use, vertical layout of the territory and formation of intermediate insulating layers on landfills with household waste. Ashes from Krasnoyarskaya TPP-2 produce construction foam and gas blocks, paving stones, and asphalt.

Despite the significant possibilities of using ASW for the production of building materials and products of the widest nomenclature, including cement constituents, aggregates, wall materials, road construction, etc., and a considerable amount of research on their processing available in Kazakhstan and the world, ASW processing on an industrial scale is rarely carried out in Kazakhstan. The work aims to study the physical–mechanical and microstructural properties of ASW and non-autoclaved aerated concrete with ash and slag additives to develop a promising method of processing this type of waste.

2. Materials and Methods

The object of the study is ash from ash dump of boiler house No.2 of Ust-Kamenogorsk CHPP (Ust-Kamenogorsk city, Kazakhstan). This object was formed as a result of combustion of coal from the Karazhyra field, which is composed of D-grade hard coal (long-flame) with an ash content ranging from 12 to 25%, working moisture of 12–16% and volatile matter content of 47%. The lower heat of combustion of working fuel is in the range from

4500 to 5200 kcal/kg. The quality of mined coal is determined based on the results of advanced formation geological sampling of coal in the faces prepared for mining. Technical analysis of samples obtained via different methods of sampling was performed in the accredited laboratory of JSC "Karazhyra" [23].

Ash is a grey-black dust, which remains after coal combustion, and bottom ash is a solid molten residue and visually, it is black stones of a small size. After coal combustion in the boilers of power plants, the remaining ash and slag are removed, as a rule, with the help of water and taken to special storage sites, ash dumps. The ash is placed on the ash disposal area designed for the reception and storage of ash and slag waste. The view and location of the boiler house and ash dump are presented in Figure 1.

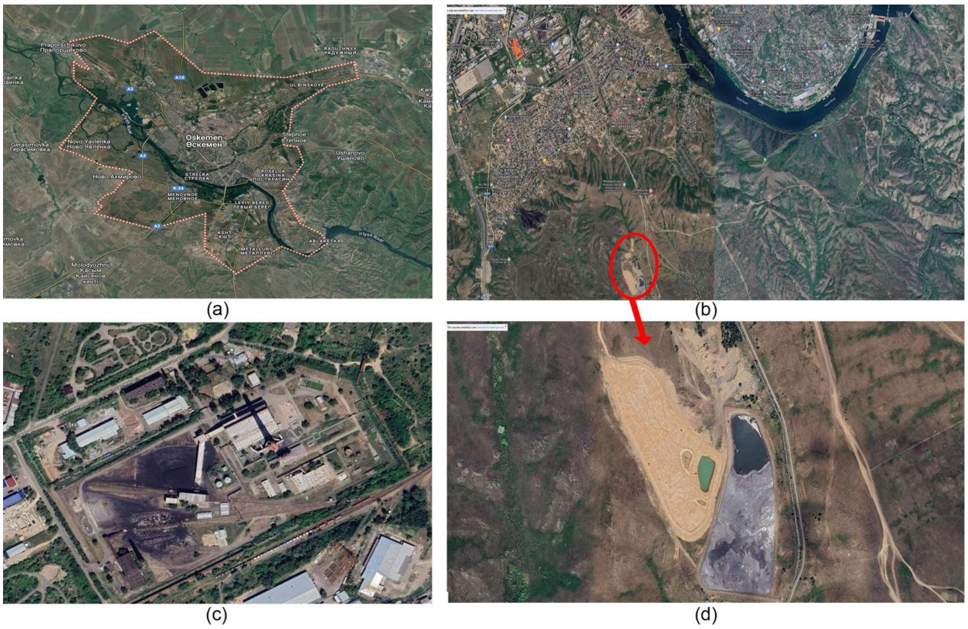


Figure 1. Overview of Ust-Kamenogorsk city and Ust-Kamenogorsk CHPP facilities (**a**) View of Ust-Kamenogorsk city. (**b**) General view of ash dump location with indication to the boiler house. (**c**) Enlarged view of boiler house No. 2 of Ust-Kamenogorsk CHPP. (**d**) Enlarged view of the ash dump.

Ash dumps are designed for long-term storage of ash and bottom ash that are in demand by consumers. Ash and slag are stored in the form of slurry in surface ash dumps (ASDs) or dry storages. In addition to waste mines and quarry workings, ravines can also be used as ash dumps. In the power industry of the Republic of Kazakhstan, surface ash ponds are mostly used. The appearance of the initial ash and slag is shown in Figure 2.

Figure 2. ASH samples from the ash dump of boiler house No. 2 of the Ust-Kamenogorsk CHPP.

To conduct studies of microstructural properties of ash and slag washers, samples in the form of pellets were prepared (Figure 3). The initial powder sample was placed in a mould with a diameter of 30 mm, filled with epoxy filler, mixed, dried, and then the obtained product was ground and polished. To conduct studies of physical and mechanical characteristics of ash-and-slag concrete samples, the following methods were used (Figure 4).

(**a**) (**b**)

Figure 3. Samples for physical–chemical studies: (**a**) sample number 1; (**b**) sample number 2.

Figure 4. Aerated concrete samples.

To carry out this research, we used analytical and other equipment, including the X'Pert PRO MPD X-ray diffractometer. To determine the phase composition of samples, the method of X-ray diffractometry was used, with comparison of the obtained diffractograms using the X'Pert HighScore program, which utilizes the Crystallography Open Database (COD) and the Inorganic Crystal Structure Database (ICSD). Research conditions included a temperature of 23 °C, humidity of 51%, and atmospheric pressure of 100.1 kPa.

Determination of all physical and mechanical parameters was carried out according to the requirements of normative documents on test methods. Grain composition of ash-and-slag cement was determined according to EN 933-1 [24], the specific surface of fine-grained ash-and-slag cement and residue on sieve No. 008 was determined according to EN 196-6 [25], bulk density of ash-and-slag cement was determined in the dry state according to EN 1097-3 [26], and uniformity of volume change was carried out in a mixture with Portland cement at a ratio of 1:1 (cement:ash) according to EN 196-3 [27] by boiling samples in water. The results of physical and mechanical tests are given in Table 1.

Table 1. Physical and mechanical parameters of ash and slag.

Name of Indicators	Actual Values of Indicators
Determination of uniformity of volume change, mm	4.5
Humidity, %	0
Bulk density (specific gravity), kg/m^3	1140
True density, kg/m^3	2112
Specific surface (m^2/kg)	253
Particle size distribution, % on sieves (mm) from	from 2.5 to <0.16

The results presented in Table 1 summarize the physical and mechanical parameters of ash-and-slag cement, highlighting its suitability for further studies and applications in non-autoclaved aerated concrete production. The uniformity of volume change, bulk density, and specific surface values align with the required standards, providing a solid foundation for subsequent analyses.

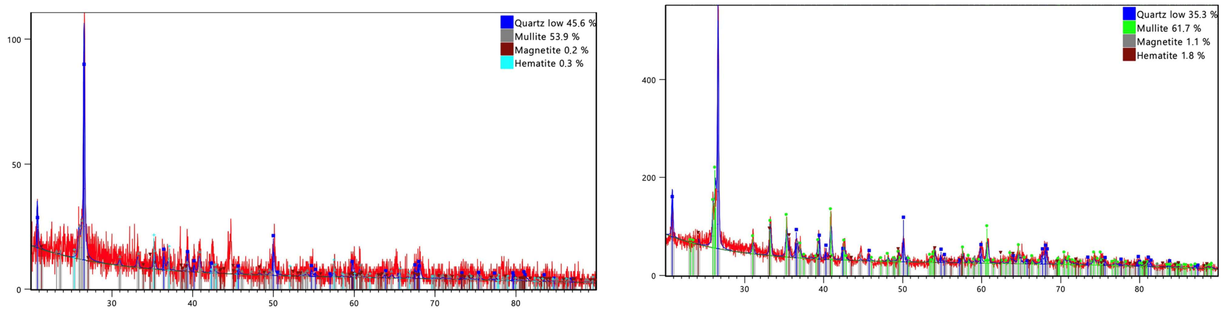
The results of studying the chemical composition of ash and slag are presented in Table 2.

Table 2. Chemical composition of ash and slag.

Sample Name	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	SO_3	$Na_2O{\cdot}K_2O$	Loss on Ignition
Ash-and-slag UK CHPP	51.27	22.49	9.32	2.95	1.69	0.95	0.93	4.67	5.63

The physical and mechanical characteristics and porous structure of aerated concrete with ash and slag additives were studied by X-ray diffraction analysis, scanning and optical electron microscopy. The spectra of ash and slag mixture samples obtained with the X'Pert PRO X-ray diffractometer (Figure 5) demonstrate that in all cases, the main components are oxides of silicon, iron and aluminium in the form of quartz, mullite, magnetite and hematite. The samples differ only in the amount of these or those minerals. In ash and slag from the ash dump, iron oxide compounds prevail and much fewer silicon oxides are reported. The main feature of ash and slag is the presence of the X-ray amorphous glassy phase in their composition. Glass formation is connected with the high temperature of solid fuel combustion, as a result of which natural quartz, a part of fuel, can melt, and lead to rapid cooling. Mullite is an aluminium silicate $3A1_2O_3$*$2SiO_2$, which is formed by high-temperature firing of silicates.

It is known [28] that fly ash is a heterogeneous material produced by the combustion of pulverised coal in thermal power plants and its phase and mineral composition include (i) an inorganic component, which is amorphous and crystalline; (ii) an organic component consisting of semi-coke (slightly altered, semi-coke and caked particles) and organic minerals; and (iii) a liquid component. Characterisation of fly ash is usually carried out using several techniques. However, scanning electron microscopy (SEM) is the best method and, along with X-ray diffraction, one of the most widely used methods for identification and characterisation of phases in fly ash, especially using SEM equipped with an energy dispersive detector. Ash exhibits variable composition and particle distribution depending on the sampling location. To investigate these differences, the samples were analyzed using a JSM-6390LV scanning electron microscope equipped with an INCA energy dispersive microanalysis system (Figure 6). Sample No. 1 represents a fresh ash-and-slag mixture directly from the furnace, while Sample No. 2 consists of aged ash-and-slag material collected from the ash dump.



(**a**) (**b**)

Figure 5. X-ray diffractometry spectra of ash and slag mixture: (**a**) fresh ash-and-slag sample from the furnace (current sample); (**b**) aged ash-and-slag sample from the ash disposal area (stored sample), (The red line represents the measured diffraction pattern, while the colored markers in the legend indicate the identified phases and their corresponding proportions).

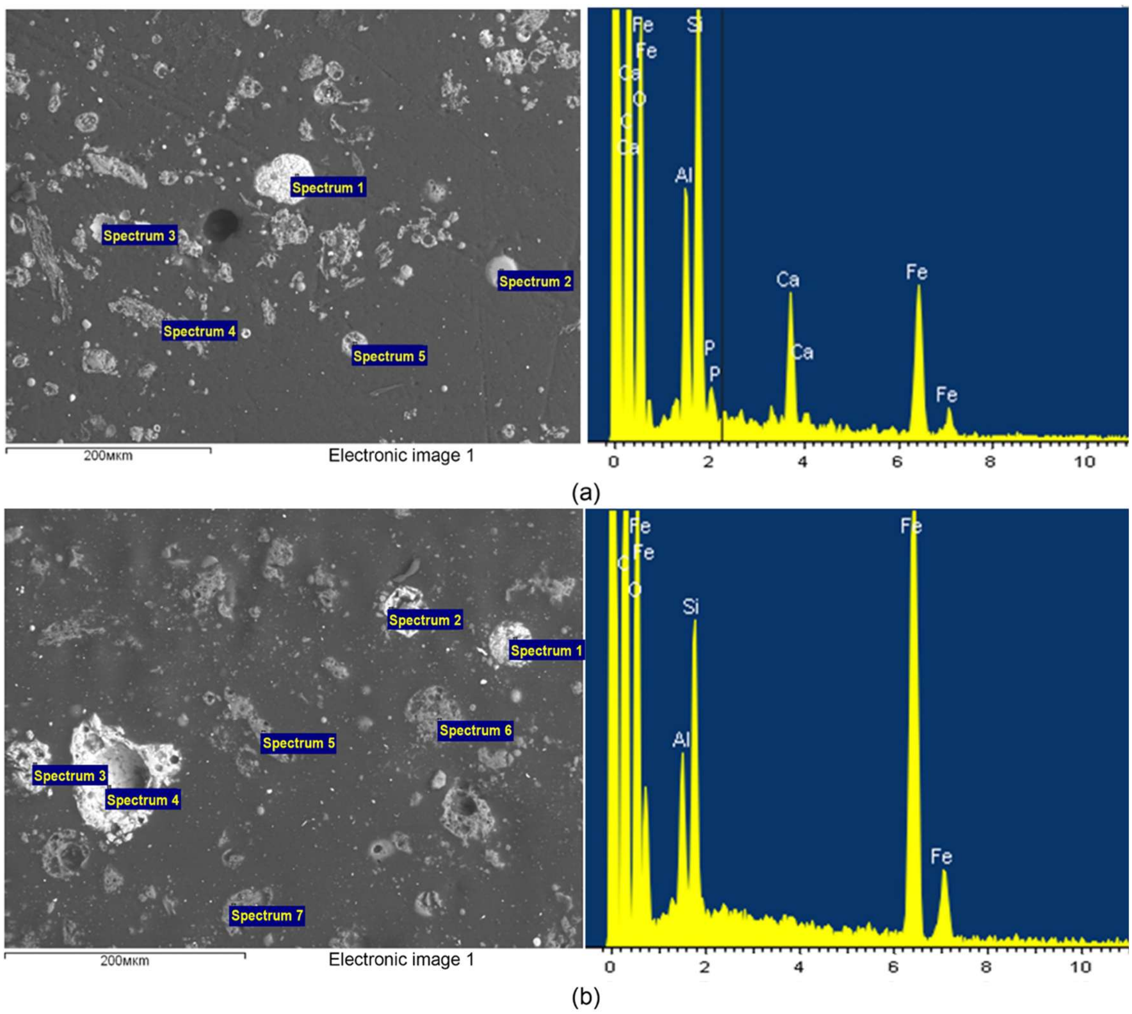


Figure 6. Images of ash and slag samples, obtained with a scanning electron microscope: (**a**) fresh ash-and-slag sample from the furnace (current sample); (**b**) aged ash-and-slag sample from the ash disposal area (stored sample).

The energy dispersive X-ray (EDX) analysis method was employed for elemental mapping of the samples. While EDX is limited to surface-level detection and cannot provide bulk compositional information, it is highly effective for identifying surface morphology and elemental distribution. These limitations highlight the need for complementary techniques, such as X-ray diffraction (XRD), to obtain a complete characterization of the samples. The choice of EDX is supported by its rapid analysis capability and precision in detecting key elements, making it particularly suitable for the preliminary assessment of heterogeneous materials like ash and slag.

The micrographs show that there are some differences in the surface morphology of the samples and the amount of the main constituents of ASW. In the current samples from the furnace, a relatively large number of coarse particles are found. They consist of coal, vitreous agglomerates and minerals (especially quartz). The SEM images of fly ash obtained can be used to describe the type of microspheres; however, only the composition and surface morphology can be evaluated using SEM techniques.

The authors of reference [29] proposed the use of image analysis using standard algorithms and artificial intelligence with both open source and commercial packages (such as ImageJ, Fiji or MATLAB). Recently, the application of neural networks provided increasingly effective image analysis and, among the different types of neural networks available today, the Self-Organising Maps (SOMs) of Kohonen seem to be among the most promising, given their capacity to receive many images as inputs and reduce them to a low number of neuronal outputs that represent all the input characteristics in a lower-dimensional space. We obtained a large series of images of ash and slag samples by means of studies on the Olympus BX-51 optical microscope with the Mineral C7 mineralogical analysis system (Figure 7).

Figure 7 shows the microstructure of aerated concrete samples with varying ash and slag content. It can be observed that increasing the ash and slag content from 25.5% to 31.5% improves pore distribution and enhances the material's strength [30]. The images obtained using a SEM clearly reveal denser and more homogeneous structures, explaining the increase in strength. These results confirm the effectiveness of using ash-and-slag additives in aerated concrete and their positive impact on the mechanical properties of the material.

The experimental samples of aerated concrete were prepared in the laboratory of the Competence and Technology Transfer Center in the field of construction at Serikbayev East Kazakhstan Technical University. Five different mixtures were prepared for the study, with ash-and-slag waste content varying from 25.5% to 31.5%. The main components used were Portland cement, quicklime, phosphogypsum, and a foaming agent. The mixtures were prepared according to established standards and methodologies, ensuring uniform distribution of additives throughout the mass.

The neural network model was developed using input data that included the chemical composition of ash-and-slag waste, specifically the content of oxides such as SiO_2, Al_2O_3, Fe_2O_3, and CaO; the percentage content of ash-and-slag waste in the mixture, ranging from 25.5% to 31.5%; the physical parameters of the samples, including density, porosity, and surface area; the results of mechanical tests, such as compressive and tensile strength values; and microstructural characteristics obtained using SEM and XRD, including pore size and distribution as well as the presence of crystalline phases. This data set was used for training and validating the Mask R-CNN neural network architecture to analyze and predict the microstructural characteristics of aerated concrete.

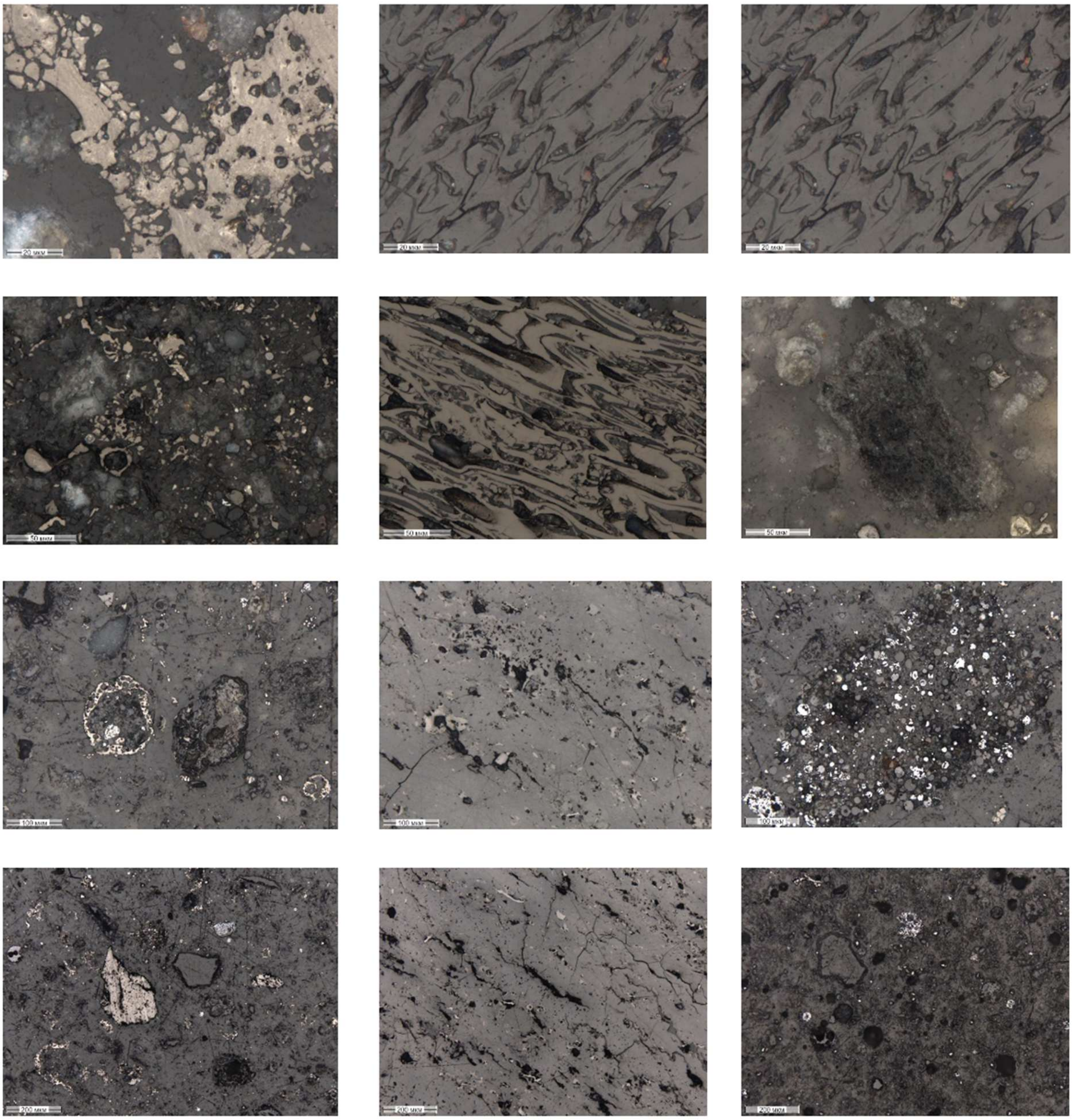


Figure 7. Images of ash and slag samples from the ash dump, obtained using an Olympus optical microscope at varying magnification from 20 to 200 μm.

3. Results

The effect of the amount of introduced ash-and-slag mixture on the compressive strength of aerated concrete is shown in Figure 8. The data presented in this figure were obtained from the experimental results of the present study, which involved testing various mixtures with ash-and-slag content. These findings are based on laboratory-scale experiments conducted to evaluate the relationship between ash-and-slag content and the compressive strength of non-autoclaved aerated concrete.

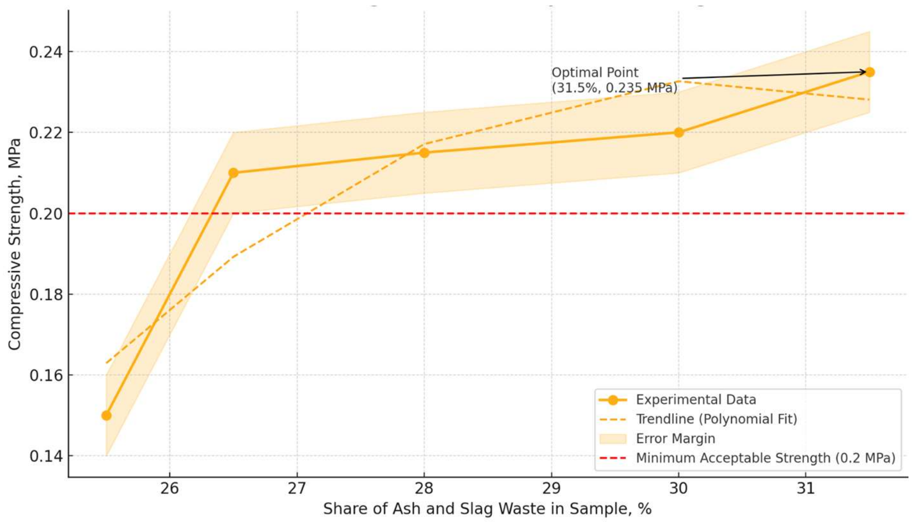


Figure 8. Effect of the amount of ash and slag mixture on the compressive strength of aerated concrete.

Figure 8 illustrates the effect of increasing the ash-and-slag mixture content from 25.5% to 31.5% by weight on the compressive strength of NAAC. The compressive strength improves significantly, rising from 0.15 MPa to 0.235 MPa. The polynomial trendline highlights a consistent upward trend, reflecting the microstructural enhancements observed in Figures 5 and 6, such as improved pore distribution and matrix densification. The inclusion of ash-and-slag additives enhances the mechanical properties of NAAC. It supports environmental sustainability by reducing the harmful impact of industrial waste disposal on soil and water–air environments.

Additionally, the annotated optimal point (31.5%, 0.235 MPa) demonstrates the highest observed strength in the study, while the shaded error margin represents potential variability in results. Including a threshold line at 0.2 MPa emphasizes the material's suitability for applications requiring minimum strength criteria. However, the variability in ash-and-slag waste composition remains a challenge, highlighting the necessity for innovative predictive methodologies to accurately forecast the properties of aerated concrete and ensure consistency in large-scale production. The ongoing research aims to develop an innovative technique to pre-predict the composition of aerated concrete with high accuracy. To activate this technique, it is determined that a minimum amount of data needs to be collected, consisting of 10,000 images of aerated concrete. These images are analyzed using computer vision and deep learning techniques, providing a training sample with sufficient variability to train the neural network and identify complex patterns in the material structure. The selection of 10,000 images is based on established practices in machine learning and image analysis, which suggests that this range provides a robust dataset for training deep learning models to achieve reliable and accurate predictions. Advanced machine learning techniques, including the Mask R-CNN neural network architecture, have contributed to significant progress in predicting the microstructural features of aerated concrete. This advancement plays a key role in manufacturing processes, opening opportunities to assess the quality of the finished product and account for possible changes in material composition during the manufacturing phase. A schematic representation of the aerated concrete composition prediction process is shown in Figure 9. To visualise the process of predicting the composition of aerated concrete, a schematic diagram was developed based on the analysis of the collected dataset using the Mask R-CNN neural network. The images accurately identify different structural elements in the material, including different types of pores and inclusions. Once the model training and validation process is complete, the study moves to the prediction phase where the model determines the microstructural composition of aerated concrete. This allows us not only to assess the quality of the material, but also to identify the features of the composition that affect its characteristics. The obtained data can be used for further improvement of the production process and for adaptation of the material formulation to the requirements to its operational properties. The final assessment of product quality can contribute to improving both the products and their creation processes.

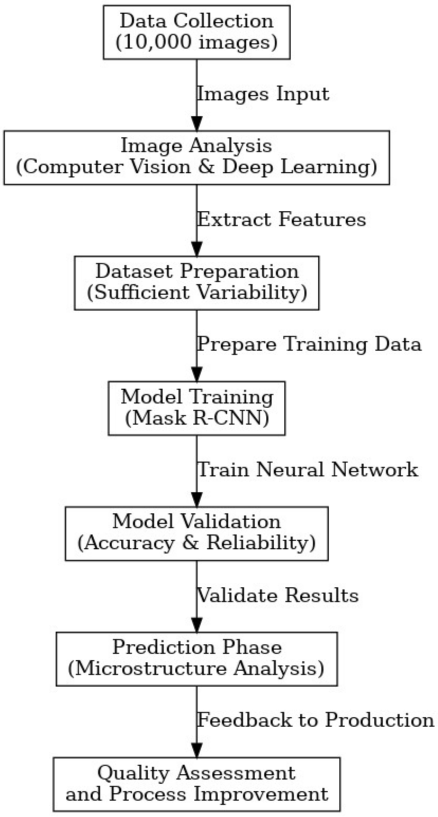


Figure 9. Prediction process for aerated concrete composition using machine learning.

Figure 9 illustrates a schematic representation of the prediction model for the composition of aerated concrete using the Mask R-CNN neural network architecture. It is important to note that this model is currently a conceptual framework and has not yet been fully validated with experimental data. The model's primary objective is to predict the microstructural characteristics of aerated concrete based on a comprehensive dataset of images and physical properties.

The preliminary results from the initial training of the neural network are promising, indicating the potential for accurately identifying different structural elements within the material. However, further validation and refinement of the model is necessary to ensure its reliability and accuracy. We plan to conduct extensive experimental validation of this prediction model and aim to present the detailed results and findings in a subsequent publication. This future study will focus on the model's performance metrics, including prediction accuracy, training and validation processes, and the use of confusion matrices to assess the model's effectiveness in real-world applications.

4. Discussion

This study investigates the incorporation of ASW into NAAC, offering significant dual benefits: effective utilization of industrial waste and enhancement of material performance. The results highlight notable improvements in the physical, mechanical, and microstructural properties of NAAC when ASW content is optimized, supporting its potential for widespread application in sustainable construction.

The compressive strength of NAAC increased from 1.45 MPa to 2.35 MPa as the ASW content rose from 25.5% to 31.5%. This improvement is attributed to the densification and homogenization of the material matrix, as confirmed by SEM and XRD analyses (Figures 5 and 6). The uniform distribution of pores at higher ASW content enhances mechanical stability and thermal insulation, crucial for structural and energy efficiency in construction. This improvement positions NAAC as a superior alternative to traditional autoclaved aerated concrete, offering competitive performance at lower production costs.

The utilization of ASW addresses pressing waste management challenges while reducing the environmental footprint of construction materials. The chemical composition of ASW—predominantly oxides of silicon (51.27%) and aluminum (22.49%)—makes it an ideal additive for NAAC production. Integrating ASW into concrete reduces reliance on natural resources, leading to cost savings. Furthermore, the non-autoclaved production process eliminates the need for high-pressure autoclaves, resulting in lower energy consumption and enabling small-scale, localized production facilities. This makes NAAC particularly suitable for regions with limited industrial infrastructure, enhancing its global applicability.

Integrating neural networks, specifically the Mask R-CNN architecture, significantly advances NAAC research. By analyzing a dataset of over 10,000 microstructural images, the neural network accurately predicts pore distribution and structural characteristics. This capability enhances quality control, enabling manufacturers to fine-tune material compositions to meet specific performance criteria. Additionally, predictive modeling provides valuable insights for optimizing production processes, potentially reducing variability in ASW composition caused by coal quality and combustion conditions.

Despite these promising findings, the study identifies several challenges. Variability in ASW composition remains a critical issue, necessitating the development of robust predictive tools to ensure consistency in material properties. Moreover, while laboratory-scale experiments provide compelling evidence of NAAC's potential, large-scale industrial trials are essential to validate the feasibility of these methods in real-world applications. Including stress–strain analyses and further exploration of ASW's interaction with other components could provide a deeper understanding of its impact on material performance.

The successful integration of ASW into NAAC aligns with global sustainability goals by mitigating waste disposal issues and conserving natural resources. Reducing greenhouse gas emissions and diverting ASW from landfills contribute substantially to environmental stewardship. Moreover, the potential to replace traditional raw materials with ASW offers a scalable and cost-effective pathway to sustainable construction practices worldwide, positioning NAAC as a key material in the transition toward a circular economy.

5. Conclusions

This study confirms the feasibility and effectiveness of utilizing ASW in producing NAAC, offering a sustainable solution for the construction industry. The incorporation of ASW at an optimal content of 31.5% resulted in a compressive strength of 2.35 MPa, significantly enhancing material performance and demonstrating its suitability for environmentally friendly and durable construction applications.

The use of ASW addresses critical challenges, including industrial waste management and environmental impact reduction, while highlighting the economic advantages of the non-autoclaved production method due to its lower energy and material requirements. A particularly intriguing aspect of this study is the application of machine learning technologies, such as the Mask R-CNN neural network, which has provided valuable tools for predicting microstructural characteristics and optimizing material composition.

Despite these promising findings, challenges such as the variability in ASW composition and the need for large-scale industrial validation remain. This underscores the ongoing need for future research and development in this field. The focus should be on refining these technologies and adapting methods to various ASW sources, paving the way for broader application of NAAC in sustainable construction.

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