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Short Review Article

A Short Review on Sodium Aluminosilicates: Natural Sources, Synthesis, and Applications

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ABSTRACT

This review presents contemporary perspectives on the nature, synthesis methods, and application areas of sodium aluminosilicates as one of the most in-demand classes of silicate materials. Geochemical mechanisms of the formation of sodium-containing aluminosilicates in magmatic, metamorphic, and sedimentary systems are considered, including pressure-induced structural transformations of amorphous phases, features of crystallization of minerals of the nepheline group, and the role of alkali elements in the evolution of the silicate network. Experimental and technological approaches to the synthesis of sodium aluminosilicates are summarized, ranging from geopolymerization and alkaline activation of technogenic wastes to thermal treatment of ashes, slags, and biomass. Special attention is paid to the mechanism of formation of sodium-aluminosilicate hydrate (N-A-S-H) gels, the influence of activator composition, phase transformations, and the possibilities for controlling the structure and properties of the resulting materials. The review demonstrates a wide range of applications of sodium aluminosilicate systems, including construction and composite materials, sorption and catalytic processes, protective and functional coatings, water treatment, soil stabilization, and the utilization of technogenic wastes. Prospects for the development of energy-efficient technologies for producing sodium aluminosilicates from alternative raw materials are outlined, along with approaches to enhancing the durability, structural stability, and functionality of these materials for industrial and environmental applications.

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Content

1. Introduction

Sodium aluminosilicates constitute a broad class of inorganic framework compounds whose structure is based on a three-dimensional network of [SiO_4] and [AlO_4] tetrahedra stabilized by Na^+ cations. This architectural framework determines their wide variability in both natural and synthetic systems, including minerals of the nepheline group, zeolitic structures, amorphous N-A-S-H gels, and glass-ceramic materials [1-3]. Interest in sodium aluminosilicates is driven by their key roles in geochemical processes of the lithosphere, as well as by the possibilities for the controlled synthesis of materials with tailored functional properties for catalysis, sorption, ion exchange, the construction industry, and environmental technologies [4-6]. Natural sources of sodium aluminosilicates include magmatic and metamorphic rocks rich in nepheline and sodalite, as well as secondary minerals formed during the weathering of silicate matrices [2,7]. Their structural evolution under the effect of pressure, temperature, and the chemical composition of pore solutions serves as a fundamental model for understanding the formation of aluminosilicate phases with different coordination environments and degrees of polymerization

[1,3]. Additional insights into natural formation mechanisms are provided by studies of clayey, biomorphic, and eutectic silicate systems, which make it possible to trace the migration of Na^+ and Al^{3+} and their involvement in the construction of stabilized aluminosilicate frameworks [6-8]. In addition to natural sources, considerable interest is focused on the industrial production of sodium aluminosilicates from alternative mineral and technogenic raw materials. Synthetic approaches include alkaline activation of aluminosilicate wastes, geopolymerization of ash-slag materials, alkaline hydrolysis of silicate-containing systems, organo-inorganic hybrid processes, and the formation of porous aluminosilicate frameworks via controlled crystallization [9-13]. It has been established that variation in the composition of alkaline activators, temperature, silicon-to-aluminum ratio, and the presence of modifying ions makes it possible to control the structure and properties of N-A-S-H gels, zeolite-like phases, and glass-ceramic sodium aluminosilicates [11-16].

Sodium aluminosilicates are widely applied due to their thermal stability, chemical inertness, and ion-exchange capacity. They are used in water treatment processes, adsorption of toxic metals, formation of corrosion barriers, development of fire-resistant coatings, synthesis of Fischer-Tropsch catalysts, production of geopolymer-based construction materials, and fabrication of porous thermal insulation systems [17-22]. Particular attention is drawn to their ability to stabilize heavy metals, form durable framework structures, and participate in sorption mechanisms that determine the efficiency of environmental technologies. Despite the extensive research and growing range of applications of sodium aluminosilicates, several scientific and technological challenges remain. These challenges include controlling phase composition and structural evolution during synthesis, improving the scalability and reproducibility of alkaline activation processes, and ensuring the long-term durability and chemical stability of aluminosilicate-based materials under aggressive environmental conditions. Furthermore, a deeper understanding of the relationships between structural features, pore chemistry, and functional performance is necessary to optimize material properties further. Addressing these issues is crucial for advancing the development of sodium aluminosilicate materials and expanding their practical use in industrial, environmental, and construction-related applications.

2. Natural Sources of Sodium Aluminosilicates

2.1. Structural and coordination evolution of the aluminosilicate matrix in geological systems

The natural formation of sodium aluminosilicates represents a multistage geochemical process controlled by transformations in the coordination environment of aluminum and by the degree of polycondensation of the silicate-oxygen framework. The general compositional features and structural relationships of sodium aluminosilicates are schematically illustrated in **Figure 1**. According to high-temperature and high-pressure modeling data [1], amorphous aluminosilicate systems exhibit a transition from predominantly tetrahedral AlO_4 coordination to distorted octahedral and five-coordinated motifs (AlO_5/AlO_6) with increasing external pressure. Densification of the polymeric Al-O-Si network is accompanied by a decrease in porosity, redistribution of charge density, and the formation of thermodynamically stable structural fragments capable of acting as precursors to future crystalline phases. These processes are closely linked to the natural mineral formation of sodium aluminosilicates such as nepheline, sodalite, and sodium-bearing zeolites. An increase in the degree of polycondensation of SiO_4 tetrahedra and reorganization of Al-O-Si linkages determine the stability of aluminosilicate matrices under deep geological conditions, which is consistent with mechanisms of lithospheric melt differentiation [1,2].

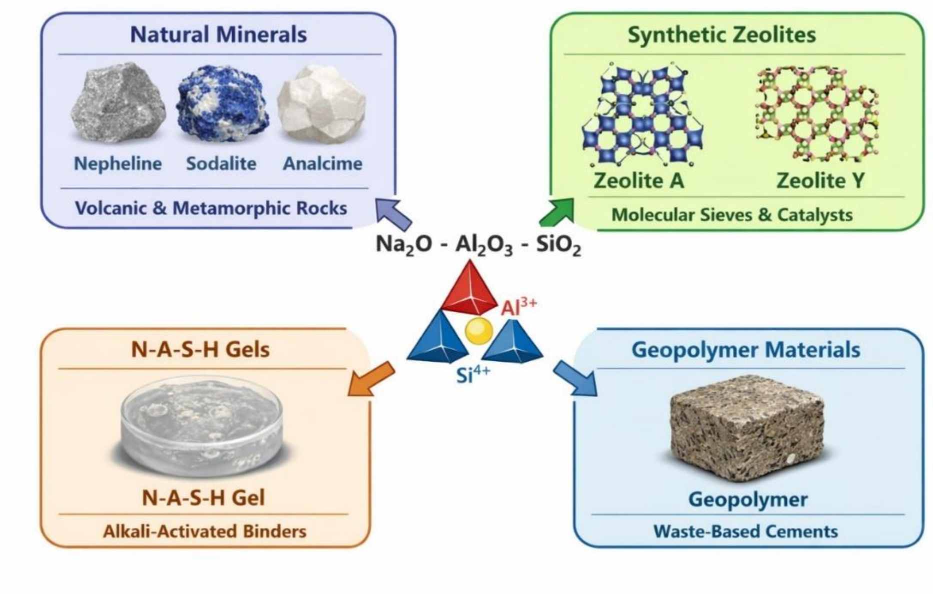

Figure 1. General compositional schemes of sodium aluminosilicates

This highlights the critical role of pressure and alkaline environments in the structural evolution of Na-Al-Si systems.

2.2. Mineralogical analogies and the role of sodium in the geochemistry of aluminosilicates

One of the key natural sodium aluminosilicates is nepheline ($NaAlSiO_4$), which forms in alkaline igneous rocks. Its structural framework provides high reactivity due to the combination of tetrahedral AlO_4 and SiO_4 units and the presence of charge-compensating Na^+ cations involved in ion-coordination equilibria [3]. Due to their low silica content, nepheline-based systems exhibit a tendency toward the formation of metastable glasses and transitional phases. This is supported by studies of sodium aluminosilicate glasses with nepheline compositions [2], in which the incorporation of phosphate anions leads to additional modification of the aluminum coordination environment.

2.3. Geochemical migration of alkali elements and the formation of Na-Al-Si phases

The migration of sodium and aluminum under natural conditions is controlled by a combination of solubility, sorption, and complexation processes in clayey, volcanogenic, and sedimentary systems. As shown in [6], normalization with respect to aluminum reveals stable coupled relationships between Na, Al, and Si concentrations, indicating the co-accumulation of these elements within layered silicate matrices. This points to the existence of a geochemical conveyor that promotes the nucleation of aluminosilicate phases under conditions of low-temperature diagenesis. An important contribution to the understanding of the thermodynamics of Na-Al-Si systems has been made by studies of eutectic equilibria in silicates [4], according to which sodium is capable of significantly lowering the melting temperature of aluminosilicate melts and stabilizing, upon cooling, structures of the sodalite, analcime, and related zeolite types. This demonstrates that the Na^+ involvement in melts determines the energetic profile of the natural synthesis of aluminosilicates. New hypotheses regarding biomolecular influences on mineral formation have been proposed in [7], where it is shown that organic matrices, including DNA, are capable of initiating the morphogenesis of carbonate-silicate phases. Despite the focus on Ba/Ca systems, similar mechanisms may be relevant to the early stages of aluminosilicate compound formation, including Na-bearing forms, under protogeological conditions.

2.4. Technogenic analogues of natural aluminosilicates and their significance

Many technogenic aluminosilicate systems serve as model analogues of natural minerals in terms of structure and reactivity. Studies of modified kaolin subjected to high-temperature calcination in the presence of NaCl [8] have shown that sodium intercalation and chloride-induced disruption of $Al_2Si_2O_5(OH)_4$ layers lead to the formation of activated aluminosilicate matrices closely resembling natural phases such as metakaolinite and analcime. Technogenic wastes of the energy industry - such as fly ash and ash-slag materials - represent attractive raw resources for the reconstruction of Na-Al-Si structures due to their high contents of amorphous SiO_2 and Al_2O_3. Studies [9,10] demonstrate that the extraction of SiO_2 from red mud and the subsequent production of soluble sodium silicates are accompanied by the formation of structural motifs analogous to those of natural aluminosilicates. These results confirm that technogenic aluminosilicates can act as chemically and structurally relevant analogues of natural minerals.

3. Synthesis of Sodium Aluminosilicates

Synthesis of sodium aluminosilicates involves various physicochemical approaches, differing in raw material origin, processing conditions, and the nature of the resulting aluminosilicate phases. Despite the diversity of reported methods, the majority of synthesis routes can be classified into several generalized categories based on the activation mechanism and thermal regime. **Table 1** summarizes the main synthesis approaches for sodium aluminosilicates discussed in this review, highlighting the typical raw materials, dominant phase assemblages, and key technological features of each method. This classification provides a concise framework for comparing different synthesis strategies and illustrates the versatility of sodium aluminosilicate systems obtained from both natural and technogenic sources.

3.1. Alkaline activation of silicate raw materials and the role of sodium activators

Modern technologies for the synthesis of sodium aluminosilicates are based on the alkaline activation of aluminosilicate and technogenic raw materials, leading to the formation of polycondensed N-A-S-H gel phases. Studies show that variation in the nature of sodium-containing activators determines the structure and phase composition of the final product. In particular, changing the molar ratio of sodium acetate to NaOH results in significant restructuring of the coordination environment of aluminosilicate gels, which is reflected in the formation of crystalline phases and the mechanical strength of hybrid alkali-organic slag-based compositions [11].

Table 1. Main synthesis approaches for sodium aluminosilicates

Synthesis approach	Raw materials	Main formed phases	Key features
Alkaline activation	Fly ash, slag, and metakaolin	N-A-S-H gel	Low-temperature synthesis and high mechanical strength
Hydrothermal synthesis	Aluminosilicate precursors	Zeolite-like Na-Al-Si phases	Controlled crystallinity and porosity
Thermal treatment	Ashes, slags, and biomass residues	Glass-ceramic sodium aluminosilicates	Improved thermal stability
Alkali-assisted processing of wastes	Red mud, industrial residues	Amorphous and semi-crystalline Na-Al-Si phases	Waste utilization and environmental sustainability

The use of sodium aluminate as an activator also demonstrates high reactivity toward silica-containing metallurgical wastes. Application of $NaAlO_2$ intensifies the dissolution of amorphous SiO_2 and promotes the formation of structural motifs characteristic of N-A-S-H gel phases [12]. Similar trends are observed during the alkaline activation of fly ash and granulated blast-furnace slag with sodium and potassium silicate solutions: the presence of Na_2SiO_3 accelerates the polycondensation of SiO_4 and AlO_4 tetrahedra and the formation of an ordered aluminosilicate matrix [13].

Cross-interactions of sodium with aluminosilicates are also important in mixed systems. The addition of $CaCO_3$ to Na_2SO_4-activated cements alters the acid-base balance of the medium and affects the formation of calcium and sodium aluminosilicate hydrates [14]. In multicomponent compositions (Mg-Zn-Al-Si), the presence of sodium determines the structure of polysilicate aluminum-magnesium-zinc complexes (PSAMZ), which are stabilized during hydrolysis and subsequent condensation in aqueous solutions [15].

Under conditions of electrolytic oxidation, sodium participates in the formation of surface aluminosilicate films on Al-Si alloys, where it regulates the thickness, porosity, and phase purity of the coating [16]. These data confirm the universal role of the Na^+ ion as a key mediator in the synthesis of aluminosilicate structures of various origins [11-16].

3.2. Activation of technogenic raw materials and processing of industrial wastes

The use of fly ash, slags, red mud, and ash residues enables the formation of aluminosilicate materials with minimal energy input. The addition of sodium aluminate to fly ash enhances the polycondensation of N-A-S-H tetrahedra and densification of the gel matrix, thereby improving the mechanical properties of alkali-activated systems [17]. Alkaline treatment of high-silica coal gangue in the presence of sodium reagents leads to the destruction of the original crystalline structure and the formation of amorphous sodium aluminosilicates analogous to geopolymeric materials [18]. In $MgO-Al_2O_3-SiO_2-H_2O$ systems, Na^+ ions act as structure-forming agents for low-temperature aluminosilicate hydrates, stabilizing nascent phases and accelerating polycondensation processes [19]. An additional promising direction involves producing aluminosilicate glass-ceramic foams from secondary aluminum wastes, where sodium plays a key role in foaming and glass-phase crystallization processes [20].

The transition to biogenic raw materials is also of considerable interest: the processing of agricultural and municipal wastes enables the synthesis of zeolite Y that fully matches the morphology of commercial sodium aluminosilicates [21]. Similarly, the use of thermally activated red mud leads to the formation of single-component binders containing typical N-A-S-H structures [22].

Under gas-evolving conditions, metallic aluminum present in municipal solid waste incineration residues promotes pore formation in aluminosilicate granules, thereby expanding the possibilities for producing lightweight materials [23]. Thus, technogenic processing becomes a key direction in the synthesis of next-generation sodium aluminosilicates [17-23].

3.3. Durability of aluminosilicate systems and the effects of aggressive environments

A key factor is the chemical and thermal durability of aluminosilicate composites. Studies of hybrid alkali-activated cements in saline environments have shown that interaction with $MgCl_2$ leads to degradation of the N-A-S-H matrix and the formation of magnesium hydrosilicates, thereby modeling natural processes occurring in evaporite systems [24]. Improved durability can be achieved through microwave treatment, which accelerates the polycondensation of aluminosilicate chains and increases structural ordering [25]. The development of additive manufacturing technologies expands the possibilities for producing sodium aluminosilicate ceramics with controlled parameters. High-precision salt cores synthesized by the binder-jetting method demonstrate structural stability even in saturated saline environments [26].

The evolution of aluminosilicate phases during carbonation is an important criterion of durability. Four-dimensional tomography shows that calcium- and magnesium-containing aluminosilicate hydrates undergo structural changes upon CO_2 uptake, forming stable carbonate phases [27]. Reactive transport modeling confirms that CO_2 diffusion and the formation of sodium and calcium carbonates govern the kinetics of structural reorganization [28]. Biogenic rice husk ash is also capable of forming stable aluminosilicate structures upon alkaline activation due to the presence of highly dispersed biogenic silica [29]. Taken together, these findings make it possible to establish a generalized model of durability for aluminosilicate composites of various origins [24-29].

3.4. Control of hydration, phase formation, and crystallization

The hydration mechanism of Si-Al systems in the presence of sodium is associated with competition between dissolution, recrystallization, and precipitation processes of mixed hydrosilicate phases. Modification of β-C_2S (dicalcium silicate) with sodium and aluminum demonstrates the formation of stable sodium and calcium aluminosilicate hydrates [30]. In calcium-activated geopolymer ceramics, the formation of mixed Si-Al gels depends on the calcination temperature and the Na^+ concentration [31].

The incorporation of calcium aluminate cements into alkali-activated systems leads to a retardation of polycondensation, which is attributed to the competing precipitation of Ca-rich phases [32]. The presence of C-S-H seeds, sulfates, and Na^+ ions regulates the morphology of fly ash microspheres, thereby affecting hydration kinetics [33]. Additional data confirm that the stabilization of red mud in the presence of silicate components leads to the formation of aluminosilicate frameworks identical to those of sodium-activated geopolymers [34]. The application of superplasticizers in alkaline media optimizes the density of the N-A-S-H gel and improves the strength of low-energy binders [35, 36].

Mixed MgO-Al_2O_3 wastes also participate in the formation of mixed aluminosilicates that stabilize the geopolymer structure [37]. In biomass ash-based systems, Na^+ stabilizes the Si-O-Al framework, confirming the characteristic structure of sodium aluminosilicates [38]. Likewise, the analysis of kaolin-based systems under foaming conditions reveals the formation of N-A-S-H and calcium-aluminosilicate hydrate (C-A-S-H) gels [39-42]. Thus, sodium controls virtually the entire spectrum of phase transitions involved in the synthesis of aluminosilicates [31-42].

3.5. Formation of porous, zeolitic, and highly structured sodium aluminosilicates

The production of aluminosilicates with structured porous frameworks represents a key research direction. Geopolymer foams based on iron ore flotation tailings have demonstrated the ability to form N-A-S-H frameworks with high adsorption capacity [43]. The use of bottom ash from municipal solid waste incinerators for the synthesis of alkali-activated materials enables the conversion of waste into highly porous aluminosilicates [44].

The mixing of red mud and blast-furnace slag results in dense sodium aluminosilicate structures exhibiting high durability [45]. Nanostructural studies indicate that pore density, the nature of Si-O-Al chains, and thermal stability correspond to those of classical N-A-S-H matrices [46]. Ordered zeolites in the potassium and sodium forms of the JBW structural type (K-, Na-JBW), synthesized using a high-silica inorganic liquid (HSIL) route, represent benchmark aluminosilicate lattices characterized by high flexibility and structural regularity [47]. Another important direction involves the utilization of glass waste, which forms aluminosilicate geopolymers with high durability [48].

Additional studies on micro-arc oxidation demonstrate the Na^+ effect on the structure of oxide-silicate coatings formed on aluminum alloys [49]. A number of investigations on refractory materials confirm the importance of sodium aluminosilicate binders in the development of high-temperature compositions [50]. Lateritic wastes can also serve as sources of Al-Si systems capable of forming geopolymer adobe materials [51,52]. Collectively, these studies highlight the wide variability of structures and synthesis approaches in this field [41-52].

3.6. Synthesis of sodium aluminosilicates in multifunctional composites and catalytic systems

The synthesis of water glass from bauxite residues provides a basis for the subsequent production of sodium aluminosilicates without the use of natural quartz [11]. Further activation of slag and ash from municipal solid waste incineration plants with Na_2SiO_3 solutions enables the production of cementitious materials with high hydration stability [53]. Functionalization of sodium-magnesium silicate hydrates with chitosan yields sorption nanocomposites with enhanced dye-binding capacity [54]. The formation of Fe-Ca-Al-Si hydrates also lead to the development of new classes of low-temperature silicate binders [55]. Alkaline fusion of low-reactivity silicate wastes makes it possible to sharply increase their reactivity and involve them in the formation of aluminosilicate systems [56]. In organobasic media, cast Mg-Y-Zn aluminosilicate ceramics are formed, modeling polycondensation processes under specific conditions [57]. Finally, anhydrous sol-gel synthesis of metal-silicate supports enables the creation of catalytic systems with enhanced activity [58]. The influence of metakaolin on the Ca_3SiO_5 hydration confirms the universality of sodium aluminosilicates as structural modifiers of cement systems [59].

3.7. Synthesis of aluminosilicates from technogenic and biogenic raw materials

Studies [60-62] addressed a method for producing silicates from rice husk, which is an abundant and highly silica-rich agricultural waste. The authors described a process (**Figure 2**) of alkaline decomposition of the biogenic raw material using microwave irradiation, which enables accelerated release of silica and the formation of a silicate solution. In [60], the parameters for preparing the mixture were reported, including 130 mL of a 1 M NaOH solution and 10 g of pre-ground and washed rice husk, and the effect of microwave activation on the efficiency of SiO_2 extraction was demonstrated.

4. Applications of Sodium Aluminosilicates

Sodium aluminosilicates exhibit a wide range of functional properties determined by the features of their crystal chemistry, the degree of polycondensation of the aluminosilicate framework, pore structure, and acid-base characteristics. Due to these parameters, they find applications in sorption, catalysis, functional coatings, construction composites, metal protection systems, water treatment technologies, soil stabilization, and composite materials. The main areas of their application, supported by an extensive body of literature data, are discussed below (**Figure 3**).

Figure 2. Synthesis of sodium aluminosilicate from rice husk

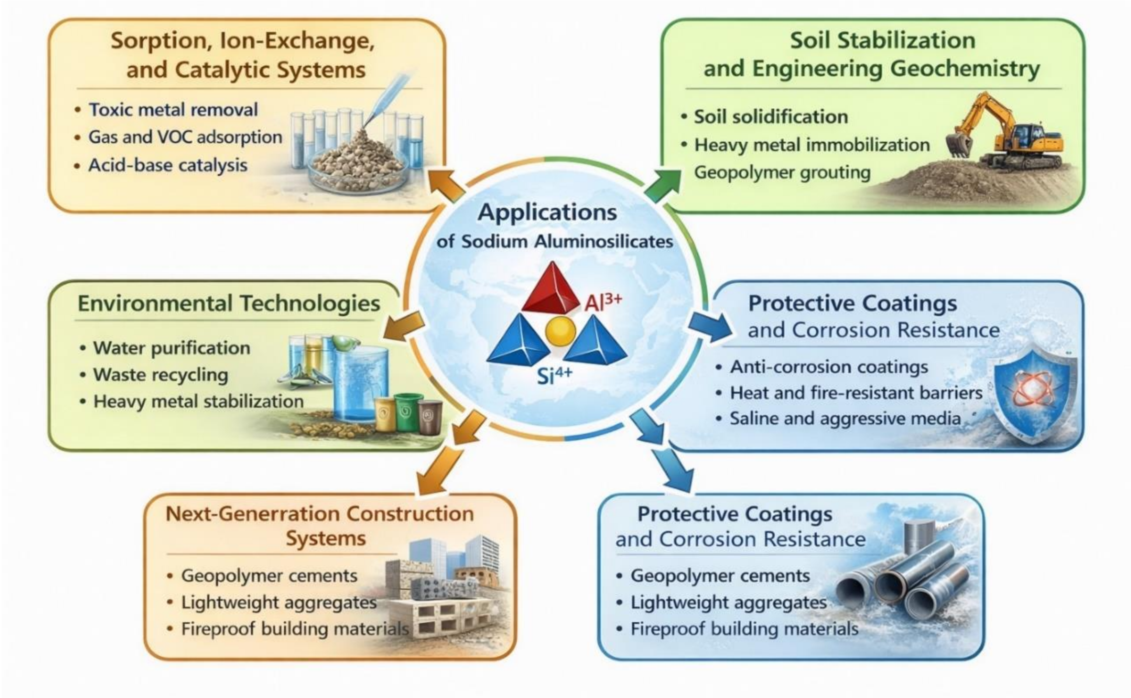

Figure 3. Schematic representation of the main application areas of sodium aluminosilicates

4.1. Sorption, ion-exchange, and catalytic systems

Due to the high degree of polycondensation of Si-O-Al networks, sodium aluminosilicates exhibit pronounced cation-exchange activity and are widely used as sorbents and catalytic supports. Geopolymer foam synthesized using iron ore flotation wastes [44] demonstrates the ability to selectively adsorb and release K^+ ions, which is attributed to the development of a mesoporous matrix stabilized by a Na^+-controlled aluminosilicate network. Significant interest is attracted by superhydrophobic anticorrosion coatings modified with zirconium silicate [63], in which the aluminosilicate phase acts as a structural reinforcing component, enhancing the chemical resistance of the surface. Similar processes are observed in systems for sealing anodized aluminum through impregnation with sodium silicate solutions and complex-forming Cr (III)/Zr (IV) ions, which ensure the formation of a high-density protective film [64].
Studies on the durability of silicate compositions [65] have shown that the stability of the aluminosilicate lattice under various cation substitutions determines the long-term performance of materials in aggressive environments. The sorption activity is most pronounced in the removal of heavy metals: sodium and calcium silicates effectively adsorb Hg (II) and Cd (II) from solutions [66], providing opportunities for the application of sodium aluminosilicates in advanced water purification systems. Hybrid nanocomposites based on sodium alginate and porous aluminosilicate clays [67] demonstrate the ability to control the release of pharmaceutical agents, while the aluminosilicate component stabilizes the polysaccharide matrix and enhances its ion-exchange capacity.

4.2. Soil stabilization and engineering geochemistry

The use of aluminosilicate additives for soil modification is associated with their ability to react with calcium-containing components and form strong cementitious compounds. Studies [68] have shown that the incorporation of Ca-Na-containing aluminosilicates promotes the development of early strength and enhances the long-term durability of compacted soil materials. An analysis of the modification of natural aluminosilicate systems is presented in the review [69], where the functionalization of bentonites with sodium forms significantly increases their sorption, catalytic, and structural properties. In geopolymer systems, aluminosilicate phases serve as the matrix responsible for the immobilization and isolation of industrial wastes. Study [70] demonstrates that aluminosilicate geopolymers are resistant to moisture and aggressive chemical environments, making them promising materials for hydraulic engineering structures. The incorporation of aluminosilicate phases into coral-based volcanic concretes significantly increases their density, strength, and corrosion resistance [71]. This effect is attributed to the formation of a multicomponent N-A-S-H/C-A-S-H-type framework that stabilizes the material structure in marine environments.

4.3. Environmental technologies: recycling, waste utilization, and environmental remediation

One of the important directions is the application of aluminosilicate systems in environmental recycling. A red mud-phosphogypsum composite investigated in [72] shows improved water-retention capacity of soils and enhanced structural stability due to the presence of aluminosilicate and sulfate compounds. Similar results are demonstrated by stabilized red mud-based cementitious materials [73].

The use of aluminosilicate fillers in an aluminum matrix enables the production of composites with increased wear resistance and thermal stability [74], thereby reducing the volume of metallic waste through extended service life of products. In micro-arc oxide coatings on Al-Mg-Sc alloys, sodium aluminosilicate ceramic phases are formed, enhancing the wear resistance and corrosion stability of the layers [75]. Aluminosilicate and silica hydrogels demonstrate the potential to enhance the fire resistance of wood by retaining moisture and forming thermally stable silicate films [76]. In reflective multilayer AlN/Al_2O_3 structures, processes of heterogeneous phase formation are observed that are comparable to aluminosilicate coatings used for thermal protection [77]. Studies [78-83] emphasize the promise of aluminosilicate materials for use in “green” technologies, ranging from cement-free binders to superamphiphobic coatings with combined thermal insulation and anticorrosion functions.

4.4. Next-generation construction systems and materials

Significant attention is devoted to lightweight thermal-insulation and structural aluminosilicate materials. The use of biomass ash and wastes from the pulp and paper industry makes it possible to obtain alkali-activated systems with a high level of mechanical strength and environmental sustainability [78]. Molecular dynamics studies [79] reveal the mechanisms of interfacial interactions in aluminosilicate binders, enabling the targeted design of geopolymer composites with predictable strength and durability. Aluminosilicate zeolites derived from thermal power plant (TPP) fly ash exhibit high efficiency in the removal of organic dyes from wastewater [39], demonstrating the potential of secondary raw materials for producing highly effective sorbents. Complex multicomponent Al_2O_3-$ZrSiO_4$ coatings formed by the PEO method are enriched with an aluminosilicate phase, which improves their structural stability under extreme conditions [9]. The use of activated concrete waste allows the development of high-density aluminosilicate systems with high strength and a low carbon footprint [80].

4.5. Protective coatings, corrosion resistance, and interactions in saline environments

In hydration-carbonation processes, aluminosilicate phases exhibit resistance to aggressive ionic environments. Enhanced fire resistance of polymer composites is achieved through the incorporation of aluminosilicate fillers, which reduce the degree of thermal degradation [81]. Basalt fiber-reinforced concretes with aluminosilicate binders demonstrate increased durability in organically contaminated environments [82]. Reported study [83] highlights the role of aluminosilicate compositions in flotation separations, where silicate structures participate in the dolomite depression . The use of sodium silicate in combination with natural surfactants contributes to a reduction in the leaching of toxic components from thermal power plant ash [84]. Sodium silicates also exhibit inhibiting properties in corrosive environments, reducing the degradation of steel 45 in NaCl solutions [85]. The chemical interaction of silicate ions with lead carbonates in drinking water [86] confirms the potential use of sodium silicates in preventing secondary contamination of water supply systems. Aluminosilicate refractories occupy a key position in metallurgy. Study [87] demonstrates that aluminosilicate compositions provide high thermal resistance and chemical stability under aluminum production conditions. In addition, investigations of the structural formation of aluminosilicate phases in complex $MgO-Al_2O_3-SiO_2$ systems confirm their role in the development of refractory coatings resistant to thermal shock and corrosion.

5. Conclusion

An analysis of the literature devoted to sodium aluminosilicates and related silicate systems shows that this class of compounds combines unique structural, sorption, catalytic, binding, and thermal-resistance properties, providing broad opportunities for both fundamental research and industrial application. In the first part of the review, the mineralogical nature of aluminosilicate raw materials, their distribution in the Earth's crust, and the characteristics of natural forms serving as the basis for the subsequent production of sodium aluminosilicates were discussed. Despite the diversity of natural sources, recent trends increasingly emphasize the processing of technogenic wastes (thermal power plant fly ash, bauxite residues, and metallurgical slags), making aluminosilicate systems a significant component of the sustainable development concept. The analysis of studies devoted to synthesis methods has shown that the key directions remain hydrothermal processes, sol-gel technologies, alkaline activation, and geopolymerization, which enable control over the structure and functional characteristics of the materials. Particular attention is given to the modification of aluminosilicates with organic and inorganic additives, the formation of nanostructured forms, and the development of complex composites. This opens prospects for enhancing material activity and durability, as well as for expanding the scope of their technical applications. The studies reviewed on the practical applications of aluminosilicates demonstrate their strong demand in water treatment, adsorption of toxic components, corrosion protection of metals, cementitious and geopolymer binders, catalysis, refractory materials, and ceramic products. Particularly promising are directions related to environmental technologies, including waste utilization, wastewater treatment, stabilization of ash-slag materials, and reduction of heavy metal emissions. The most active development of aluminosilicates is observed in materials science and construction technologies, where there is growing interest in low-temperature binders, composite geopolymers, and functional coatings. Overall, the review confirms the sustained scientific and practical significance of sodium aluminosilicates as multifunctional materials. Further progress in this field requires in-depth investigation of the relationships between composition, structure, and properties of aluminosilicates, as well as the implementation of advanced modification approaches and scalable synthesis methods. An equally important challenge remains the optimization of processing routes for natural and technogenic raw materials to obtain high-performance aluminosilicate materials targeted for industrial applications within the transition to green technologies.

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Conflict of Interest

Author's declared that there is no conflict of interest exists

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