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Classification, Terminology and Abbreviations



Guang Ye and Frank Dehn

Abstract This chapter introduces the classification of AAMs, the terminology used in the following chapters and provides the notation of abbreviations.

1 Classification

Alkali-activated materials (AAMs) are a class of mineral-based, inorganic, and non-metallic binders that harden and set through the addition of alkaline activators (e.g., alkali hydroxides or alkali silicates) to aluminosilicate-rich source materials (precursors). Alkali-activated materials are primarily classified based on their calcium content, alkali activator, reaction mechanisms and the resulting reaction products.

High-calcium systems (CaO > 10 wt.%): High-calcium systems are derived from calcium-rich precursors ((CaO) content > 10 wt.%). These prosecutors include metallurgic by-products such as ground granulated blast furnace slag (GGBFS), ladle slag, and ferronickel slag, as well as by-products of combustion processes like high-calcium fly ash (Class C fly ash) and other industrial residues. When alkali hydroxides and/or alkali silicates are used as activator, the chemical reaction in high-calcium systems involve both hydration (similar like in Portland cement systems) and polymerization. The reactions result in the formation of complex multi-phase systems that include calcium silicate hydrates (C–S–H) phases with low C/S ratios [1, 2] and calcium-aluminosilicate-hydrate (C–A–S–H) phases [3–5]. Additional reaction products depend on the nature of the activators used: tetracalcium aluminate hydrate (C_4AH_{13}) forms in both alkali silicates-activated and alkali hydroxide-activated slag system [2]. Hydrotalcite and strätlingite (C_2ASH_8) are primarily found in alkali hydroxide-activated slag [6, 7].

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Low-calcium systems (CaO ≤ 10 wt.%): Low-calcium systems, commonly referred to as geopolymers [8], are derived from precursors with calcium oxide (CaO) content ≤ 10 wt.%. These systems utilize aluminosilicate-rich processors such as metakaolin, class-F fly ash, calcined clays, silica fume, red mud and agro-industrial wastes. The choice of precursor significantly affects the reactivity and final properties of the system. When activated with alkali hydroxides (e.g., NaOH, KOH) and/or alkali silicates (e.g., sodium silicate), the reaction primarily involves polymerization. This process leads to the formation of a three-dimensional, amorphous to semi-crystalline aluminosilicate gel, primarily composed of sodium-alumino-silicate-hydrate (N–A–S–H) [3, 9, 10]. Secondary reaction products are also found including various zeolites, such as hydroxysodalite [11], Na-chabazite [12], and zeolite [13]. The reaction products in low-calcium systems are highly dependent on the nature of the activator, its molar ratio, and curing conditions, such as temperature and humidity. Elevated curing temperatures (e.g., 40–80 °C) typically accelerate the polymerization process, enhancing the development of the aluminosilicate gel network and promoting the formation of secondary phases.

To account for regional variability in precursor materials, the precursors discussed in this report are further categorized into:

Conventional precursors: Discussed in Chap. "Conventional Precursors and Activators", these include widely available industrial by-products like fly ash and ground granulated blast furnace slag (GGBFS).

Non-Conventional precursors: Discussed in Chap. "Non-conventional Precursors and Activators", these encompass less commonly used materials such as agro-industrial wastes sugarcane bagasse ashes, by-products of combustion processes like municipal solid waste incineration ashes.

The reaction mechanisms and resulting reaction products vary significantly depending on the type of activators used. These differences are explored in detail in the corresponding chapters.

The classification of alkali-activated materials is summarized in Table 1.

1.1 Terminology and Abbreviations

Alkali-activated binders (AABs)—Inorganic binders produced by mixing aluminosilicate-rich precursors with alkaline activators, leading to hardened materials with cement-like properties.

Alkali-activated concrete (AAC)—A specialized concrete that uses alkali-activated binders (AABs) in place of Portland cement (PC). This system incorporates aluminosilicate-based precursors and alkaline activators to achieve cement-like hardening and strength.

Alkali-activated cements (AACs)—Cements produced by reacting aluminosilicate-rich precursors (e.g., blast furnace slag, fly ash, metakaolin) with alkaline activators

Table 1 The classification of alkali-activated materials

	High-calcium systems (CaO > 10 wt.%)	Low-calcium systems (CaO ≤ 10 wt.%)
Precursors	• Metallurgic activities by-products (ferrous slag, i.e. ground granulated blast furnace slag (GGBFS), ladle slag, electric arc furnace slag, ferronickel slag • By-products of combustion processes (class-C fly ash)	• By-products of bauxite mining (red mug) • By-products of combustion processes (class-F fly ash, coal bottom ashes, municipal solid waste incineration ashes) • Agro-industrial wastes (rice husk ashes, palm oil fuel ashes, sugarcane bagasse ashes) • Silica fume • Metakaolin • Calcined clays
Reaction mechanism	Combination of hydration and polymerization	Polymerization
Reaction products	• Ca-poor C–S–H phases (C/S = 0.9–1.2) • C–A–S–H phases • Hydrotalcite, C_4AH_{13}, C_2ASH_8	• Sodium-alumino-silicate-hydrate (N–A–S–H) • Hydroxysodalite, Na-chabazite,, zeolite P, zeolite Y

(e.g., hydroxides or silicates). They harden into a cementitious matrix and can serve as a lower-CO_2 alternative to traditional Portland cement.

Alkali-activated fly ash (AAFA)—A specialized category of alkali-activated binders that uses fly ash as the primary aluminosilicate precursor. When mixed with alkaline activators (e.g., sodium or potassium hydroxide and/or silicate), fly ash undergoes a chemical reaction to form a hardened, cementitious matrix.

Alkali-activated materials (AAMs)—Inorganic binders formed by reacting aluminosilicate-rich precursors (e.g., fly ash, blast furnace slag) with alkaline solutions, offering cement-like strength and durability with potentially lower CO_2 emissions than traditional Portland cement.

Alkali-activated blast furnace slag (AAS)—A cement-like binder produced by mixing ground granulated blast furnace slag (GGBFS) with alkaline activators, forming a hardened material with potentially lower CO_2 emissions than traditional Portland cement.

Blast furnace slag (BFS)—A by-product generated during the production of iron in a blast furnace. When iron ore, limestone, and coke are heated at high temperatures, impurities separate from the molten iron and form a molten slag layer. Primarily composed of oxides of silica (SiO_2), alumina (Al_2O_3), calcium (CaO), and smaller amounts of other elements. Its chemical composition makes it reactive under certain conditions (e.g., with Portland cement or alkaline activators).

Calcined hydrotalcite-type layered double hydroxides (CLDH)—are derived from hydrotalcite-like materials, which are lamellar (layered) compounds consisting of positively charged metal hydroxide layers balanced by interlayer anions. Upon calcination, these layered structures partially collapse, creating mixed metal oxides with high surface area and active sites.

Calcium (sodium) aluminosilicate hydrate (C–(N–)A–S–H)—is a binding phase similar to the well-known calcium silicate hydrate (C–S–H) found in traditional Portland cement systems, but with additional aluminum (A) and, often, sodium (N) in its structure. This phase forms an amorphous or poorly crystalline gel with a layered or chain-like arrangement, providing strength and durability in alkali-activated and hybrid cement systems.

(Coal) fly ash (FA)—is a by-product of burning pulverized coal in power plants, collected from the flue gases by electrostatic precipitators or other filtration devices. It is typically a fine powder that can improve certain properties when used in concrete, mortar, or other binder systems. Primarily composed of oxides of silica (SiO_2), alumina (Al_2O_3), iron (Fe_2O_3), and calcium (CaO), with trace amounts of other elements. The glassy phase and spherical particle shape often enhance workability and can contribute to pozzolanic or latent hydraulic reactions in cementitious materials.

Fiber reinforced alkali-activated concrete (FRAAC)—is an alkali-activated concrete (AAC) in which fibers (e.g., steel, glass, polypropylene, basalt) are incorporated to enhance mechanical and durability properties. Like traditional fiber-reinforced concretes, FRAAC derives its binding phase from alkali-activated binders rather than Portland cement.

Fibre reinforced polymer (FRP)—FRP refers to a composite material composed of a polymer matrix (e.g., epoxy, polyester, vinyl ester) reinforced with high-strength fibres (e.g., glass, carbon, aramid, basalt). This combination provides a balance of lightweight form, high tensile strength, and chemical resistance.

Geopolymer concrete (GPC)—is a type of alkali-activated concrete in which an aluminosilicate-rich precursor (e.g., fly ash, metakaolin) is combined with alkaline activators (often sodium or potassium silicate and hydroxide). It forms a hardened binder through geopolymerization, creating a three-dimensional, cross-linked network typically described as N–A–S–H (sodium–aluminosilicate–hydrate) gel.

Glass wool (GW)—is a fibrous material made by spinning or drawing molten glass into very fine fibers. Commonly composed of silica (SiO_2), combined with other oxides (e.g., soda-lime glass components) to achieve specific thermal and mechanical properties.

Global warming potential (GWP)—is a metric used to compare the climate impacts of different greenhouse gases by quantifying how much heat each gas traps in the atmosphere relative to carbon dioxide (CO_2).

Ground Granulated Blast Furnace Slag (GGBFS)—refers to blast furnace slag (BFS). It is a fine, powdery material formed by quenching molten blast furnace slag from iron production and then grinding it into a powder. It is commonly used as a partial or full replacement for Portland cement (PC) or as a key precursor in alkali-activated systems.

Interfacial transition zoom (ITZ)—is the thin region of material surrounding aggregates or fibers within a cementitious or composite matrix. It often exhibits distinct microstructural and chemical characteristics compared to the bulk matrix, making it a critical interface that influences overall mechanical and durability properties.

Life cycle assessment (LCA)—is a systematic framework used to evaluate the environmental impacts associated with all stages of a product's or system's life cycle—often referred to as "cradle to grave." It considers raw material extraction, manufacturing, transportation, use, maintenance, and end-of-life disposal or recycling.

Layered double hydroxides (LHDs)—are lamellar (sheet-like) materials composed of positively charged metal hydroxide layers intercalated with charge-balancing anions. They typically conform to a general formula $[M^{2+}_{1-x}M^{3+}_{x}(OH)_2]^{x+}(A^{n-})_{x/n} \cdot mH_2O$, where M^{2+} and M^{3+} are di- and trivalent metal cations, and A^{n-} is an interlayer anion (e.g., CO_3^{2-}, NO_3^-).

Loss of ignition (LOI)—is a measure of the mass loss that occurs when a material (e.g., cement, fly ash, soil, or other mineral-based samples) is heated to a high temperature, typically in the 900–1000 °C range, for a specified period. It indicates the presence and quantity of volatile components such as moisture, organic matter, and carbonates that decompose or evaporate under these conditions.

Magic angle spinning nuclear magnetic resonance (MAS NMR)—is a solid-state NMR technique that involves spinning the sample at a specific angle (the "magic angle," approximately 54.74°) relative to the main magnetic field. This spinning rapidly averages out anisotropic (direction-dependent) interactions, such as chemical shift anisotropy and dipolar couplings, resulting in narrower NMR signals that resemble those seen in solution-state NMR. It is a powerful method in solid-state spectroscopy, offering high-resolution insights into the local structure and dynamics of a wide range of materials that are otherwise difficult to characterize using traditional solution-state NMR.

Metakaolin (MK)—is a highly reactive pozzolanic material produced by the thermal activation (typically 600–900 °C) of kaolinite clay ($Al_2Si_2O_5(OH)_4$). The calcination process drives off bound water (dehydroxylation), resulting in an amorphous, high-surface-area aluminosilicate phase suitable for pozzolanic or alkali-activation reactions.

Municipal solid waste (MSW)—refers to everyday waste generated by households, commercial establishments, institutions, and small industries in urban or municipal areas. It encompasses a diverse range of materials, including food scraps, paper, plastics, metals, glass, and textiles.

Municipal solid waste incineration (MSWI)—involves combusting municipal solid waste (MSW) at high temperatures to reduce its volume and potentially recover energy in the form of heat or electricity. This process addresses the growing need to manage ever-increasing quantities of municipal waste, especially where landfilling space is limited.

Sodium aluminosilicate hydrate (N–A–S–H)—refers to the primary binding gel that forms in many alkali-activated (geopolymer) systems when aluminosilicate precursors (e.g., fly ash, metakaolin) react with sodium-based alkaline solutions. Chemically, it contains linked silica (Si) and alumina (Al) tetrahedra, balanced by sodium (Na^+) cations, and structurally resembles an amorphous or poorly crystalline three-dimensional framework.

Network forming oxide (NWF)—are oxides—such as silica (SiO_2), boron oxide (B_2O_3), phosphorus pentoxide (P_2O_5), and germanium oxide (GeO_2)—that form a continuous, interconnected three-dimensional network in glass and certain ceramic systems. In these structures, the oxide anions bridge the network-forming cations (e.g., Si^{4+}, B^{3+}, P^{5+}), creating strong bonds responsible for the rigidity and basic framework of the material.

Network modifying oxide (NWM)—are oxides—such as sodium oxide (Na_2O), calcium oxide (CaO), potassium oxide (K_2O), or magnesium oxide (MgO)—that, when added to a glass or ceramic system, disrupt the continuous network structure formed by Network Forming Oxides (e.g., SiO_2, B_2O_3). Their presence introduces "non-bridging" oxygens, altering the original bonding framework and changing the material's properties.

Palm oil fuel ash (POFA)—is a by-product generated from burning palm oil residues (fiber, shell) as fuel in palm oil mills, primarily to produce energy for mill operations. Typically collected from boiler furnaces, POFA often contains partially burned organic matter as well as inorganic oxides derived from the biomass. POFA generally has significant amounts of amorphous silica, making it potentially reactive in cementitious or alkali-activated systems.

Paper sludge ash (PSA)—is a by-product from paper recycling or manufacturing processes. It is produced when the residual sludge (composed of cellulose fibers, fillers like clay or calcium carbonate, and other organic/inorganic substances) is incinerated to reduce volume and recover energy. PSA often contains significant amounts of calcium oxide (CaO) or calcium carbonate ($CaCO_3$). In some cases, High-calcium PSA can partially replace Portland cement, contributing to reduced clinker usage and associated CO_2 emissions.

Polycarboxylate Ether superplasticizers (PCE)—are high-range water-reducing admixtures used in high performance concrete like self-compacting concrete and ultra-high performance concrete to improve workability while reducing the water-to-cement ratio. They are synthesized from polycarboxylic acids and modified polyethylene glycol (PEG) chains, typically resulting in a comb-like molecular structure.

Poly-melamine sulphonates (PMS)—are a class of superplasticizers (high-range water reducers) often referred to as sulfonated melamine formaldehyde (SMF). They are synthesized by condensing melamine with formaldehyde and then sulfonating the product, creating polymers with sulfonate groups that readily adsorb onto cement particles.

Poly-naphthalene sulphonates (PNS)—are a class of superplasticizers (high-range water-reducing admixtures) used in concrete to improve flow and workability. Derived from naphthalene sulfonic acid polymers, they often appear as dark brown liquids or powders and are sometimes referred to as sulfonated naphthalene formaldehyde (SNF).

Portland cement (PC)—is the most widely used hydraulic binder in construction, primarily composed of clinker—an intermediate product of limestone (calcium carbonate) and clay (silica and alumina) heated in a kiln—along with a small percentage of gypsum. The key mineral phases in clinker include tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF).

Portland cement concrete (PCC)—is a composite material produced by mixing Portland cement (the primary binder) with water, fine aggregates (sand), coarse aggregates (gravel or crushed stone), and often chemical or mineral admixtures (e.g., plasticizers, fly ash). The cement paste (cement + water) binds the aggregates together, hardening over time through hydration reactions to form a solid, load-bearing mass.

Polypropylene (PP)—is a thermoplastic polymer made by polymerizing propylene (C_3H_6). It is characterized by a structure where methylene ($–CH_2–$) and methine (–CH–) groups alternate, resulting in high crystallinity and relatively low density. PP Offers a balance of stiffness and impact resistance, which can be tailored by compounding or copolymerization.

Polyvinyl alcohol (PVA)—is a water-soluble, synthetic polymer produced by the hydrolysis of polyvinyl acetate (PVAc). The degree of hydrolysis influences PVA's solubility, crystallinity, and other physical properties. PVA fibers can reinforce cementitious materials (e.g., in engineered cementitious composites) to control crack width and enhance toughness.

Refuse-derived fuels (RDF)—is a type of fuel produced by processing various types of waste materials, primarily municipal solid waste (MSW). The process involves removing non-combustible components such as metals, glass, and plastics to create a fuel that can be used as an alternative to conventional fossil fuels. RDF serves as a means to recover energy from waste, thereby reducing the volume of waste sent to landfills and promoting sustainable waste management practices.

Representative volume elements (RVE)—is a volume or region within a heterogeneous material (e.g., concrete, composites, rock) chosen so that its statistical properties accurately reflect the material's overall behavior at a larger scale. When modeled or simulated, the RVE should capture all the essential microstructural features—such

as aggregates, voids, fibers, or grains—so that the results can be extrapolated to the entire structure without needing to analyze every micro-scale detail.

Rice husk ash (RHA)—is a high-silica, pozzolanic by-product from the combustion of rice husks, offering significant benefits as a supplementary cementitious material in concrete. Its use enhances mechanical properties and durability while promoting environmental sustainability by recycling agricultural waste and reducing the carbon footprint of construction materials.

Scanning electron microscopy (SEM)—is a powerful imaging technique that uses a focused beam of high-energy electrons to generate detailed images of the surfaces of solid materials. SEM provides high-resolution, three-dimensional-like images, making it invaluable for analyzing the morphology, composition, and topography of a wide range of samples, from biological tissues to advanced engineering materials.

Self-compacting concrete (SCC)—is a highly flowable type of concrete that can spread into place, fill formwork, and encapsulate reinforcement without the need for mechanical vibration. SCC is designed to achieve excellent workability and flowability while maintaining stability and resistance to segregation and bleeding. Its ability to flow and consolidate into complex forms makes it ideal for a wide range of applications, from intricate architectural designs to highly reinforced structural elements.

Serviceability limit state (SLS)—It is defined as the stage in the service life of a concrete member or structure in which the structural system loses its performance and usability under normal service conditions and loadings while ensuring functionality and stability. It is usually associated with an allowed crack opening $w = 0.5$ mm.

Sewage sludge ash (SSA)—is the inorganic residue obtained after the incineration of sewage sludge, which is the semi-solid by-product generated from wastewater treatment processes. SSA results from thermal treatment processes such as incineration, pyrolysis, or gasification, which aim to reduce the volume of sludge and recover energy or valuable materials.

Shrinkage reducing admixtures (SRAs)—are chemical additives formulated to minimize the drying shrinkage of cementitious materials such as concrete and mortar. They typically function by altering the surface tension of pore water, thereby mitigating capillary stresses that cause shrinkage. SRAs offer an effective approach to controlling drying shrinkage in concrete and mortar, helping improve crack resistance, structural durability, and overall service life.

Silica fume (SF)—is an ultrafine, amorphous form of silicon dioxide (SiO_2) generated as a by-product of producing silicon or ferrosilicon alloys in electric arc furnaces. Captured from flue gases, it appears as a grey, powdery material with particle sizes typically less than 1 μm, making it much finer than cement particles. With its highly reactive SiO_2 SF significantly improves the strength and durability of concrete, making it a popular choice for high-performance structures exposed to demanding service conditions.

Small amplitude oscillatory shear (SAOS)—is a rheological testing technique used to characterize the viscoelastic properties of materials by applying oscillatory shear deformations of small amplitude. It involves subjecting a material sample to oscillating shear stresses or strains and measuring the resulting stress or strain response, allowing for the determination of key viscoelastic parameters.

Sodium hydroxide (SH)—is a highly caustic and versatile strong base widely used in various industrial, commercial, and household applications. It is available in several forms, including solid pellets, flakes, granules, and aqueous solutions, each suited for specific uses based on concentration and handling requirements. Sodium hydroxide acts as a key alkali activator in alkali-activated materials by supplying hydroxide ions that dissolve aluminosilicate precursors, initiating the formation of strong binding gels like sodium aluminosilicate hydrate (N–A–S–H). This activation enhances the mechanical strength and durability of the resulting binders, making sodium hydroxide essential for the effective performance of alkali-activated concrete and other sustainable construction materials.

Sodium silicate (SS)—commonly known as *water glass* or liquid glass, refers to a group of compounds composed of sodium oxide (Na_2O) and silica (SiO_2) in various ratios. It exists in multiple forms, including aqueous solutions, gels, and solid powders, each with distinct properties and applications. Sodium silicate is valued for its versatility, chemical stability, and adhesive qualities, making it a staple in numerous industrial, construction, and consumer applications.

Stone wool (SW)—also known as rock wool or mineral wool, is an inorganic fibrous material derived from natural rocks such as basalt, diabase, or dolomite. It is primarily composed of silicates and aluminosilicates, formed into thin fibers through high-temperature melting and rapid cooling processes. SW is a highly effective insulation material renowned for its thermal and acoustic properties, fire resistance, and durability. Its versatility makes it suitable for a wide range of applications in both residential and industrial settings.

Sugarcane bagasse ash (SCBA)—is the inorganic residue produced from the combustion of sugarcane bagasse, which is the fibrous by-product remaining after extracting juice from sugarcane stalks. SCBA is generated primarily in sugar mills and bioenergy facilities where bagasse is used as a renewable energy source to generate steam and electricity.

Superplasticizers (SPs)—are high-range water-reducing admixtures used in concrete technology to enhance the workability and flowability of concrete without increasing its water content. Superplasticizers enable the production of highly workable concrete mixes, such as Self-Compacting Concrete (SCC) and high-strength concrete, by dispersing cement particles and improving the flow characteristics of the fresh concrete.

Supplementary cementitious materials (SCMs)—are finely divided materials used in concrete either as partial replacements for Portland cement or in addition to it, aiming to improve concrete properties and reduce clinker content. They typically

react chemically with calcium hydroxide (released during cement hydration) or take part in pozzolanic and/or latent hydraulic reactions, forming extra binding phases that enhance the concrete's microstructure.

Temperature stress testing machine (TSTM)—a specialized apparatus designed to simulate and measure the restrained thermal behavior of concrete (or similar materials) from the early age onward. By precisely controlling the temperature and monitoring the specimen's deformation and stresses, TSTMs help researchers and engineers understand how thermal expansion, contraction, and associated stress development affect cracking and structural integrity.

Ultimate limit state (ULS). It is defined as the stage in the service life of a concrete member or structure in which the structural system reaches the loading case scenario prior to ultimate collapse, i.e. its maximum load-bearing capacity. It is usually associated with an allowed crack opening $w = 0.5$ mm.

Vinyl copolymers (VC)—are a class of synthetic polymers derived from the copolymerization of vinyl monomers. These copolymers incorporate two or more different vinyl-based monomers into their molecular structure, enhancing and tailoring their properties for specific applications. Vinyl copolymers are versatile materials widely used in various industries, including construction, automotive, packaging, adhesives, and coatings, due to their customizable physical, chemical, and mechanical properties.

Wheat straw ash (WSA)—is the inorganic residue obtained after the combustion of wheat straw, which is the stalks left over after harvesting wheat grains. It is primarily produced as a by-product in agricultural practices, especially in regions with extensive wheat cultivation, where wheat straw is either burned for energy or disposed of as agricultural waste.

X-ray diffraction (XRD)—is an indispensable analytical tool for determining the crystallographic structure and phase composition of materials. Its ability to provide detailed, non-destructive insights into the atomic arrangement and properties of a wide range of crystalline substances makes it crucial in fields such as materials science, chemistry, geology, and pharmaceuticals.

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