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Review

Advances and prospects in rapid curing technology for geopolymers

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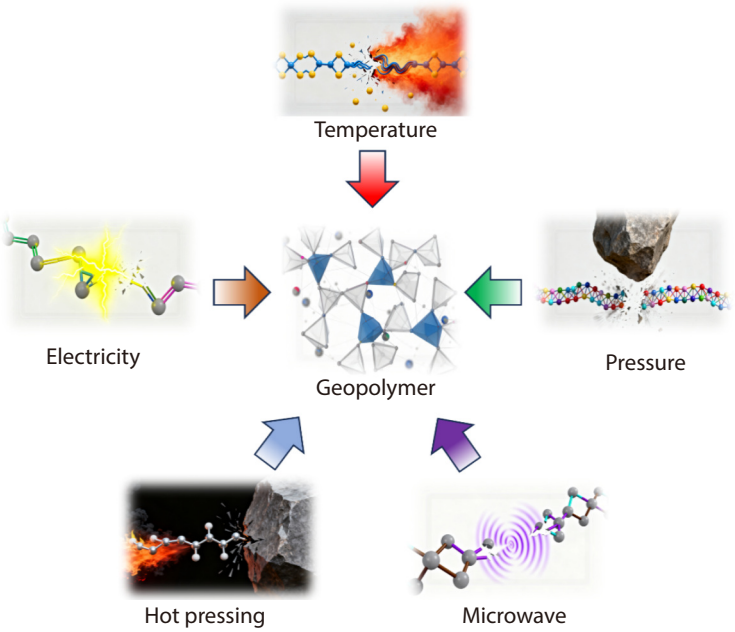
Abstract: Geopolymer is a green cementitious material formed by alkaline activation of aluminosilicate materials, offering advantages such as early strength, rapid hardening, heat and corrosion resistance, and low carbon emissions. It shows great potential for recycling solid waste and producing high-performance construction materials. However, its mechanical properties depend heavily on curing conditions, limiting its widespread application. This paper comprehensively reviews how factors like temperature, pressure, vacuum, electric field, and steam affect the mechanical properties and microstructure of geopolymers. It systematically examines both single-field curing methods (e.g., ambient, electric, microwave, vacuum, steam, high-temperature, internal, and water bath curing) and multi-field composite curing techniques (e.g., autoclave, hot-pressing, and synchronous vacuum hot-pressing curing). The findings indicate that rapid curing significantly accelerates the dissolution and polycondensation processes, enhancing early strength and microstructural density. However, improper parameter control can lead to pore coarsening, microcracking, or strength regression. Furthermore, this review summarizes reaction kinetics and structural evolution under multi-field coupling, identifies research gaps in micro-mechanisms and multi-factor interactions, and proposes future research directions. These include establishing "curing-structure-property" models, optimizing composite curing strategies, enhancing long-term durability, and advancing intelligent and sustainable curing processes, thereby supporting the scientific development and industrial application of geopolymers.



Keywords: geopolymer, rapid curing, multi-field coupling curing, mechanical properties, microstructure evolution

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1. Introduction

Geopolymer is a three-dimensional network-structured cementitious material formed through the inorganic polymerization of aluminosilicate materials under alkaline activation. Compared to ordinary Portland cement, it offers advantages including lower CO_2 emissions, reduced energy consumption, abundant and accessible raw materials, and lower production

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costs[1]. Moreover, it effectively facilitates the recycling and reuse of industrial by-products such as fly ash and slag[2-4]. Currently, geopolymer is recognized as a sustainable building material with the potential to replace traditional cement and even certain ceramic materials[5-7]. Its gel-encapsulated crystalline structure, formed through condensation polymerization, endows it with excellent thermal resistance, surpassing that of high-molecular materials and some metals. Additionally, it demonstrates mechanical strength and chemical stability comparable to ceramics[8]. In recent years, geopolymer has demonstrated extensive potential in various fields, including hazardous waste solidification[9], protective coatings[10], restoration of ancient buildings[11], construction materials[12], and interior decoration due to its superior overall performance. Although it has reached the commercial application stage, its use remains largely confined to basic applications, with large-scale engineering implementation significantly constrained by curing requirements. Ongoing in-depth research is actively advancing the development and practical application of geopolymer.

The curing process plays a critical role in the performance development of geopolymer. Its reaction mechanism resembles that of conventional thermosetting materials[13]. Early heating promotes the dissolution and depolymerization of aluminosilicates, thereby influencing the evolution of material properties. A vacuum environment facilitates rapid water migration, enhances the uniform distribution of activators, and accelerates early-stage reaction kinetics[14,15]. Pressurization helps remove excess air and water, reduces porosity, and leads to the formation of a denser alkali-activated system. Research indicates that initial impact pressure can remove approximately 65% of the entrapped air in fresh geopolymer paste[16]. Prolonging the curing time enhances the early dissolution of aluminosilicates and facilitates subsequent reaction processes. Currently, various rapid curing techniques—such as microwave curing[17], electrical curing[18], autoclave curing[19], and vacuum curing[20]—have been developed for cementitious material systems, showing strong adaptability in high-end applications of geopolymer. By conducting keyword searches, a substantial volume of highly relevant literature can be retrieved (as illustrated in Fig. 1), demonstrating that extensive research has been undertaken in this field.

The setting and hardening of geopolymer can occur across a wide temperature range. Previous studies have primarily focused on conventional room-temperature curing methods used in construction, such as standard curing ((20±2) °C, humidity≥95%) and natural curing[21-23]. However, rapid curing is more sensitive to environmental conditions and can significantly enhance the rates of depolymerization and repolymerization, leading to accelerated material hardening[24]. Rapid curing involves subjecting specimens to controlled conditions to complete the primary hydration or polymerization reactions within a few hours or even minutes, thereby enhancing early-age strength[25]. Currently, common rapid curing methods are summarized in Table 1. To mini-

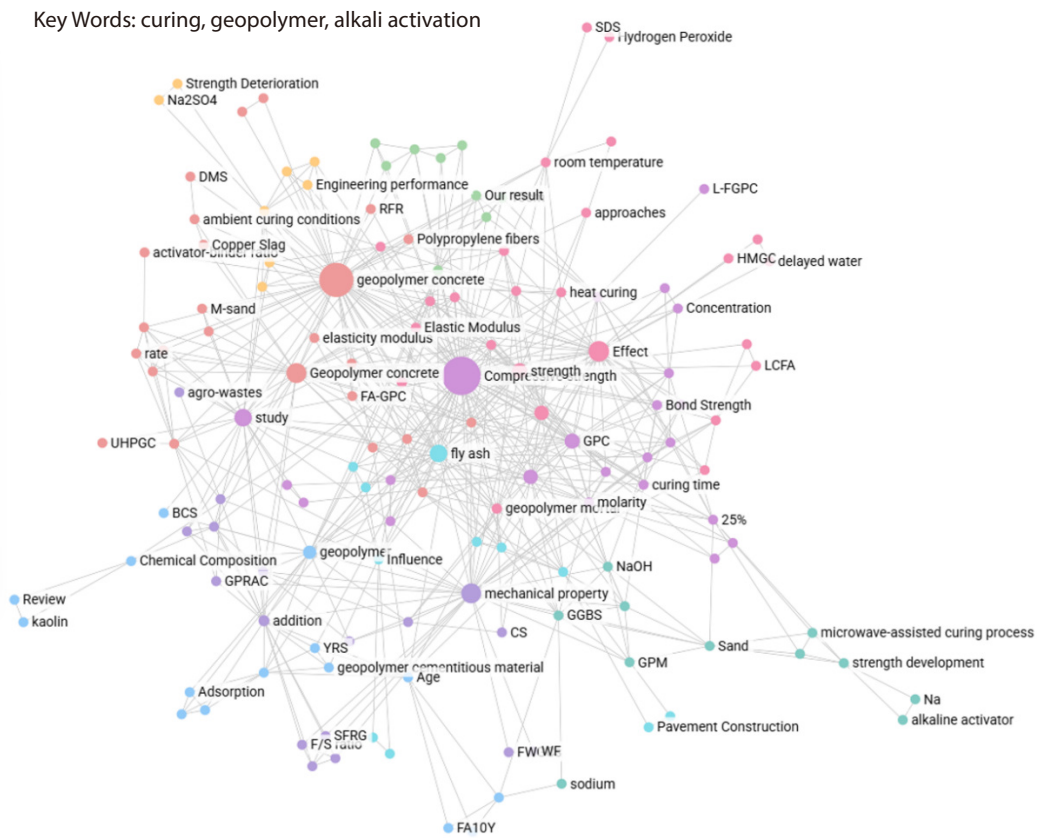

Fig. 1. Search results for strongly correlated literature in the field of geopolymer curing.

Table 1. Repercussions of diverse curing techniques on the characteristics of geopolymers.

Curing mode	Raw material/ Activator	Research result	Ref.
Autoclave	FA/ $NaOH+Na_2SiO_3$	The prepared coarse aggregate had proper angles and rough surfaces, higher strength, and better durability.	[27]
High temperature	MK/ $NaOH+Na_2SiO_3$	The kinetic energy of the system increased, the dissolution of silica-aluminate was accelerated, and the gel formation rate increased. The swelling was severe.	[28]
Microwave	FA/ $NaOH+Na_2SiO_3$	Curing was more efficient. It can accelerate the solidification process of the fresh mixed paste without affecting the final strength after curing.	[29]
Electric	FA/ $NaOH+Na_2SiO_3$	Compressive strength could reach 33.8 MPa in 2 d. The resistivity of FAG decreased with increasing temperature, which had a positive effect on the power consumption of electric curing.	[30]
Vacuum	MK/ $NaOH+Na_2SiO_3$	Release water quickly, forming low-defect porous materials with higher compressive strength. It could inhibit the formation of microcracks and reduce shrinkage.	[31]
Hot pressing	FA/ $NaOH+Na_2SiO_3$	The compressive strength at 7 d was only 10 MPa, and the strength increased by about 2.5 times at 80 °C and 3.2 MPa pressure.	[32]
Steam curing	FA+GGBFS/ $NaOH+Na_2SiO_3$	The rheological properties of the mortar improved, with better particle dispersion. The microstructure developed further, though pores became coarser, leading to reduced electrical conductivity and piezoresistivity.	[33]
Internal curing	Coral aggregate, limestone aggregate/ $NaOH+Na_2SiO_3$	Internal curing reduces carbonation and free alkali leaching in geopolymers and enhances the binder structure via secondary hydration.	[34]
Synchronous vacuum hot pressing	MK+FA/ $NaOH+Na_2SiO_3$	A new ultra-high-performance geopolymer, similar to ceramic, offers high strength, hardness, temperature resistance, and low cost.	[35]

mize performance variations caused by differences in raw materials, activators, and other factors, the same raw materials and activators were used to prepare a series of geopolymer paste samples using different rapid curing techniques. Their compressive strengths are presented in Fig. 2. Compared with normal-temperature curing, these methods can substantially shorten the curing period, accelerate the reaction process, and enhance early-age strength[26]. Furthermore, notable differences in mechanical properties are observed among samples cured under different conditions.

In recent decades, significant progress has been made in areas such as alkali-activated raw materials, alkali dosage, activator modulus, and water-binder ratio[36-38]. However, research on curing systems—particularly the mechanisms of polymerization reactions and microstructural evolution during curing—remains limited. This paper provides a systematic review of rapid curing technologies for geopolymers. Based on the number and synergy of applied physical fields, these technologies are categorized into two groups: "single-field curing" and "multi-field coupled curing". This classification criterion is fundamentally grounded in the complexity of their action mechanisms: single-field curing (e.g., thermal, pressure, vacuum, electric field) independently controls one core environmental parameter to directionally accelerate the reaction process, resulting in a relatively straightforward and clear mechanism; whereas multi-field coupled curing (e.g., hot-pressing, autoclave) aims to achieve synergistic control over reaction kinetics and microstructure under more complex conditions by integrating the advantages and mitigating the limitations of individual methods through the coordinated action of two or more physical fields, thereby yielding superior comprehensive properties. Sections 2 and 3 of this paper will elaborate on the principles, characteristics, and research progress of these two curing types, respectively, with the aim of providing a theoretical foundation and technical guidance for overcoming curing-related bottlenecks in performance control and large-scale application of geopolymers.

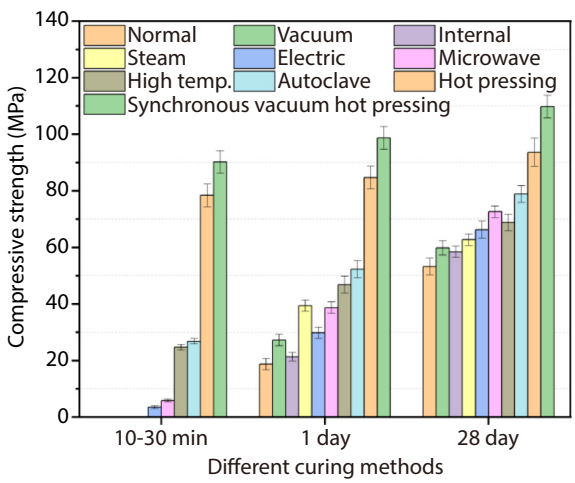

Fig. 2. Compressive strength of metakaolin-fly ash geopolymers fabricated from identical raw materials under varying curing conditions. The data are derived from a comparative experiment independently designed by the author of this article (unpublished).

2. Single curing method

In geopolymer research, clarifying the terminology for "curing" is essential. In this paper, "curing" broadly refers to the process of controlling environmental conditions to promote and regulate the geopolymer reaction and performance development. Its interpretation, however, varies with the rate and purpose: under traditional ambient curing, it resembles "maintenance"—a slow process of sustaining a suitable temperature and humidity environment. In the context of rapid curing, the focus of this study, it aligns more with "solidification",

involving the use of external energy fields or special conditions to actively accelerate polymerization, leading to rapid hardening and early strength development.

This section systematically reviews common single-field curing methods—such as ambient[39], electric[40], microwave[41], vacuum[42], steam[43], high temperature[44], and internal curing—addressing[45] their mechanisms, process features, and effects on mechanical and microstructural properties. Table 2 compares these methods in terms of principles, mechanical performance, applications, and limitations. By analyzing reaction kinetics, structural evolution, and property development under various single-parameter curing conditions, this study highlights the pivotal role of individual physical parameters and lays a theoretical basis for optimizing composite curing strategies.

2.1. Room temperature curing

Room temperature curing (RC) is the most commonly used and fundamental method for curing cement, geopolymer, and other cementitious materials[52,53]. It is typically conducted under standard environmental conditions ((20±2) °C, relative humidity≥95%). This method offers several advantages, including operational simplicity, low equipment requirements, and low energy consumption. It is well-suited for most construction sites and laboratory studies, and is widely applied in the production of ordinary building components where early strength development is not a critical requirement.

During the RC process, maintaining appropriate moisture and temperature conditions is crucial for ensuring the continuous hydration and polymerization reactions of geopolymer[54]. Moisture serves as a reaction medium in the alkali activation process and also helps prevent premature water loss from the slurry, which may result in shrinkage and cracking[55]. Insufficient ambient humidity directly leads to moisture evaporation from the sample, thereby slowing

Table 2. Comparative analysis of single curing methods.

Curing method	Core principle	Energy consumption and early-age strength	Applicable scenarios	Limitations	Ref.
Direct electric curing	Uses alternating current to uniformly heat the fresh paste from within via Joule heating, thereby accelerating ion migration and reaction kinetics.	Medium/Significant	Construction in cold environments, projects requiring high early strength, systems incorporating conductive materials	Requires a certain level of material conductivity; excessively high voltage may cause pore coarsening and strength reduction.	[46]
Microwave curing	Uses microwave electromagnetic energy to cause molecular vibration and friction within the material, generating rapid and uniform heating from the inside out.	Medium/Significant	Fly ash-based geopolymers, rapid prototyping products, laboratory and small-scale precast components	Microwave power control is critical; improper settings can easily cause localized overheating and rapid water evaporation; may limit ultimate densification.	[47]
Vacuum curing	By using a low-pressure environment to remove air and distribute components, this method improves reaction uniformity and microstructure.	Medium/Moderate	Production of high-density materials, lunar/vacuum environment construction, fundamental laboratory research	While it may accelerate free water evaporation and disrupt reaction continuity, the interaction between vacuum level, time and material composition is complex.	[48]
Steam curing	Uses near-atmospheric pressure to provide a moist heat environment, significantly accelerating early-age hydration and gel phase formation.	Medium-high/ Significant	Precast elements, low-calcium system geopolymers, projects pursuing high early strength	Prolonged heat and humidity can dissolve alkaline components, cause surface dusting, and weaken the transition zone, compromising long-term strength.	[49]
High-temperature curing	Uses high heat to accelerate aluminosilicate depolymerization and repolymerization through direct thermal input, forming a ceramic-like structure.	High/Very significant	Refractory materials, high-performance ceramic substitutes, specialized applications with stringent requirements for high-temperature stability	Susceptible to rapid water evaporation, leading to drying shrinkage and thermal cracking; requires high energy, limiting use mostly to laboratory research.	[50]
Internal curing	Uses internal water source (e.g., pre-saturated lightweight aggregates) to gradually release water during the reaction, reducing auto-shrinkage and microcracking.	Low (material itself)/Moderate (primarily through defect suppression)	High-strength geopolymers, mass concrete elements, projects requiring high crack resistance and volume stability	The release behavior of internal curing agents requires specific optimization for compatibility with different geopolymer systems.	[34]
Water bath curing	Hydrothermal conditions in water bath curing facilitate zeolite formation.	Moderate to low/ Medium	Preparation of zeolite composite materials and adsorption materials in the laboratory	The reaction pathway is dependent on parameters such as temperature and base concentration.	[51]

down the reaction kinetics and promoting the formation of a more porous and weaker microstructure. Similarly, curing temperatures lower than the standard (20±2) ℃ can significantly retard the dissolution of raw materials and the polycondensation rate, delaying strength development. Conversely, higher temperatures, while potentially accelerating early reactions, can exacerbate water loss and cracking if humidity is not meticulously controlled. Yuan et al. conducted systematic orthogonal experiments to investigate the effects of liquid-to-solid ratio, activator modulus, and fly ash content on the performance of metakaolin-fly ash-based geopolymer[56]. The results indicate that when the water-binder ratio is 0.90, the activator modulus is 1.5, and the fly ash content is 20%, the compressive strength of the sample after 28 d of normal temperature curing can reach up to 76.74 MPa, demonstrating significant potential for later strength development. Yang et al.'s research also shows that the tensile and compressive strengths of geopolymers prepared from metakaolin after 28 d of RC can reach 1.31–1.39 MPa and 30–42 MPa, respectively, suggesting that geopolymers can achieve considerable mechanical properties under appropriate formulation conditions even in conventional environments[57].

RC also exhibits notable limitations. From the perspective of the polymerization mechanism, the geopolymerization reaction proceeds at a relatively slow rate under ambient conditions. Both the dissolution of aluminosilicate precursors and the subsequent polycondensation process are constrained by the limited thermal energy available, resulting in restricted formation of early-stage gel phases and a low degree of reaction[58]. This leads to a microstructure in the final product characterized by a low cross-linking density of the amorphous gel and a substantial amount of unreacted particles. Macroscopically, this is reflected in the slow development of early-age strength, necessitating extended curing periods to achieve gradual performance improvement[59]. Such slow strength gain significantly impacts construction progress and formwork turnover efficiency. Furthermore, if the curing duration is insufficient or environmental humidity is not properly controlled, test specimens are prone to excessive early-age shrinkage, surface cracking, and deformation. These issues not only reduce the load-bearing capacity but also compromise durability and long-term performance.

In addition, RC is highly dependent on the type and proportion of raw materials[60]. For example, high-calcium systems, such as slag-based and fly ash-based geopolymers, exhibit higher reactivity and faster strength development under normal temperature conditions[61]. In contrast, low-calcium systems, such as metakaolin-based geopolymers, demonstrate slower reaction rates and rely more on extended curing periods for strength development[62]. Therefore, in practical engineering applications, it is essential to select suitable curing durations and moisture retention strategies based on the specific material system. When necessary, measures such as covering with moisture-retaining films or periodic watering can be implemented to minimize water evaporation.

2.2. High-temperature curing

High-temperature curing (HTC) refers to a curing method in which geopolymer specimens are subjected to a high-temperature environment (typically above 100 ℃) with dry or low humidity, significantly accelerating the reaction kinetics. Unlike steam or autoclave curing, HTC does not depend on steam as the main medium for heat and mass transfer[63,64]. Instead, it facilitates the depolymerization and repolymerization of aluminosilicate raw materials through direct thermal energy input, promoting the formation of a more stable, ceramic-like structure[65]. High-temperature conditions are commonly employed in oil well cement applications. Zhao et al. demonstrated that by incorporating an appropriate amount of lithium slag, the compressive strength of oil well cement after 28 d of HTC increased by 87.8%, while permeability decreased by 57.1%[66]. Elevated temperatures promote cement hydration reactions and the formation of calcium silicate hydrate (C-S-H), ultimately enhancing the strength of hardened cement paste[67].

HTC can achieve a compressive strength exceeding 100 MPa in geopolymers within hours, significantly promoting the formation of zeolite-like crystalline phases such as sodalite and nepheline, and facilitating the transformation from an amorphous gel to a crystalline-gel composite structure[68]. Miao et al. systematically compared the effects of two HTC methods—hydrothermal treatment and drying at 150 ℃—on metakaolin-based geopolymers[69]. They found that under hydrothermal conditions, the recrystallization of N-A-S-H gel in a high-temperature, water-rich environment led to increased zeolite phase formation and weakening of the gel framework, resulting in a significant strength reduction. Sun et al.'s in-depth study on the high-temperature alkaline hydration process of steel slag-based geopolymers revealed that increasing the curing temperature markedly enhanced the formation of gel products, with this promoting effect becoming more pronounced at higher alkali equivalents[70]. This indicates a synergistic interaction between high temperature and high alkalinity in accelerating the dissolution-polycondensation reaction.

At the mechanistic level, high temperature provides substantial thermal kinetic energy, greatly accelerating the dissolution and depolymerization of aluminosilicate precursors while promoting the migration and polycondensation of monomeric ions. This leads to the rapid formation of a highly cross-linked gel network. However, excessively high temperatures or prolonged durations may induce recrystallization or phase transformation of the gel into zeolitic structures, compromising the continuity of the gel framework and potentially causing strength regression. These phenomena underscore the significant role of high-temperature conditions in modulating the reaction pathway and governing the composition of the final products.

However, HTC also presents significant challenges. Elevated temperatures can rapidly accelerate water evaporation, which, if not properly controlled, may lead to drying shrinkage and thermally induced cracking, particularly in large or complex-shaped components[71]. Moreover, temperature selection must be strictly guided by the thermal stability and reaction behavior of the raw materials to avoid performance

deterioration caused by excessive sintering or phase separation[71,72]. Therefore, HTC is still primarily confined to laboratory research or specialized applications where high-temperature resistance is a critical requirement, such as in refractory materials and advanced ceramic substitutes.

2.3. Direct electric curing

Direct electric curing (DEC) is a technique that applies alternating current (AC) to specimens to accelerate the hardening process. Under the influence of an electric field, ion movement generates Joule heating due to electrical resistance, resulting in an inward-to-outward temperature gradient. This phenomenon enhances energy transfer efficiency, accelerates the reaction kinetics, and improves the early-stage mechanical properties of the material[73-75]. To prevent electrolysis, AC is typically employed in electrical curing[76]. At present, DEC is commonly used in on-site construction of ordinary concrete, particularly in cold environments, to mitigate low-temperature damage[77,78]. This technique enables uniform heating, enhances compressive strength development, and significantly reduces energy consumption[79].

Research on electro-curing of geopolymer remains relatively limited. Cai et al. investigated the effects of different conductive admixtures on the electro-curing behavior of fly ash-based geopolymer and found that the incorporation of carbon black and steel fibers can promote a more compact microstructure, thereby enhancing both compressive strength and ductility[80]. Kovtun et al. found that under conditions of a water-binder ratio of 0.40, a binder-sand ratio of 0.35, and an admixture dosage of 10% (Na_2SiO_3 and NaOH), the compressive strength of fly ash-based geopolymer reached 33.80 MPa at 2 d and 48.50 MPa at 28 d after 2 h of constant-voltage heating (10 A, 0–260 V) followed by 3 h of electro-curing[30]. Ziolkowski et al. also concluded that the compressive strength of geopolymers after short-term electro-curing would be higher than that achieved through conventional curing methods[81], a finding that was similarly reported by Kovtun et al.[30].

DEC utilizes the uniform distribution of electrical resistance in fresh paste. Under the application of AC, it increases the sample temperature by generating heat through the movement of OH^- ions, thereby promoting hydration. The ohmic thermal efficiency is influenced by factors such as the intensity of the applied electric field and the dosage of conductive materials. Compared with steam curing, DEC requires shorter curing time and consumes less energy[82]. Wadhwa et al. achieved a more uniform temperature distribution by optimizing the electrode arrangement[78]. The addition of conductive materials such as graphene[83], carbon nanotubes[84], and carbon fibers[85] can enhance the formation of conductive pathways and improve heating efficiency. The significant improvement in the early mechanical properties of geopolymers through DEC is closely related to the evolution of the pore structure.

Comparative analysis of the pore structure and pore size distribution of metakaolin-based geopolymer under different curing methods (as shown in Table 3 and Fig. 3) reveals that low-voltage DEC effectively reduces both the average pore size and total porosity. However, when the applied voltage reaches 4–7 V, both parameters exceed those observed in samples cured under normal temperature conditions. Further increases in curing voltage lead to pore expansion and a higher proportion of gel pores larger than 5 nm, indicating that high-voltage curing may promote the coarsening of the gel pore structure.

2.4. Microwave curing

Microwave curing is a process that utilizes microwave electromagnetic radiation to heat materials[87,88]. Microwaves enable the molecules within the material to absorb energy, converting electromagnetic energy into thermal energy and thereby achieving uniform internal heating. Due to their penetration capability, microwaves can heat the interior of the sample effectively, reducing the temperature difference between the inner and outer regions and promoting uniform thermal distribution. During the curing process, as moisture within the sample evaporates, a temperature gradient gradually develops from the inside to the outside[89]. At the same time, the direction of steam pressure migration caused by heating aligns with the direction of heat transfer, facilitating rapid and uniform heating of the specimen.

Compared with samples subjected to ordinary curing, high-temperature steam curing, and microwave curing, microwave-cured samples remained the highest strength as the curing age increased[90]. Leung et al. prepared concrete by mixing cement, sand, and aggregates with a water-cement ratio of 0.40[91]; after microwave curing for 4.5 h, the compressive strength reached 27.5 MPa. Microwave curing has also proven to be an effective method for enhancing the early strength of alkali-activated geopolymers. Somaratna et al. were the first to apply a household microwave oven to cure an alkali-activated system for 120 min, achieving a compressive strength of 58 MPa in fly ash mortar[92]. Shi et al. developed a multi-stage microwave curing regime for alkali-activated fly ash cementitious materials based on experimental findings, which holds significant economic potential for material development[93].

Microwave power is a key factor influencing the curing effect. Lei et al. analyzed the porosity, density, and compressive strength of geopolymers under different microwave curing powers[94]. Their research found that when the power increased from 180 W to 720 W, the mass loss of the samples

Table 3. Pore structure data of geopolymer under different curing methods[86].

Types	Ref.	3V	4V	5V	6V	7V
Average pore diameter (nm)	31	30.5	33	34	34.8	49.6
Total porosity (%)	31	29.8	33.4	32.3	34.7	49.8
Pore volume (mL/g)	0.198	0.185	0.213	0.244	0.242	0.253

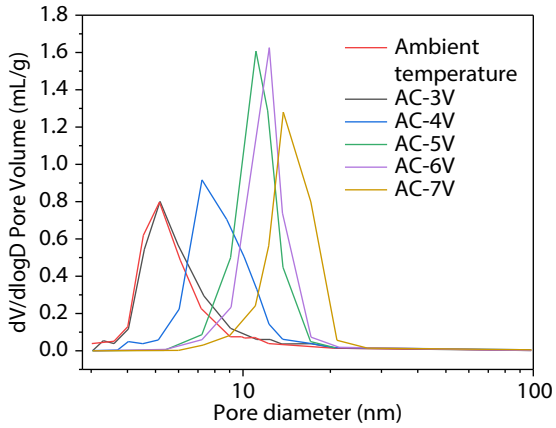

Fig. 3. Pore size distribution curves of geopolymer under different curing methods. Reproduced with permission from Ref. [86].

rose from 16.8% to 26.1% and then stabilized (as shown in Fig. 4). The strength was the highest at 180 W, and it decreased when the power was further increased. Due to the difference in dielectric properties of each component, sharp fluctuations in local temperature may occur, leading to uneven heating. Fig. 5 compares the microstructure of alkali-activated fly ash geopolymer under microwave curing and HTC conditions. During microwave curing, internal heat absorption and expansion of fly ash particles occur[95]. Additionally, the strong microwave absorption capacity of microspheres leads to a rapid increase in local temperature, which promotes the dissolution and polymerization of silicate and aluminate species[96]. In contrast, under HTC, the fly ash particles retain their original spherical morphology.

The principle of microwave interaction with matter involves the absorption of electromagnetic energy by the

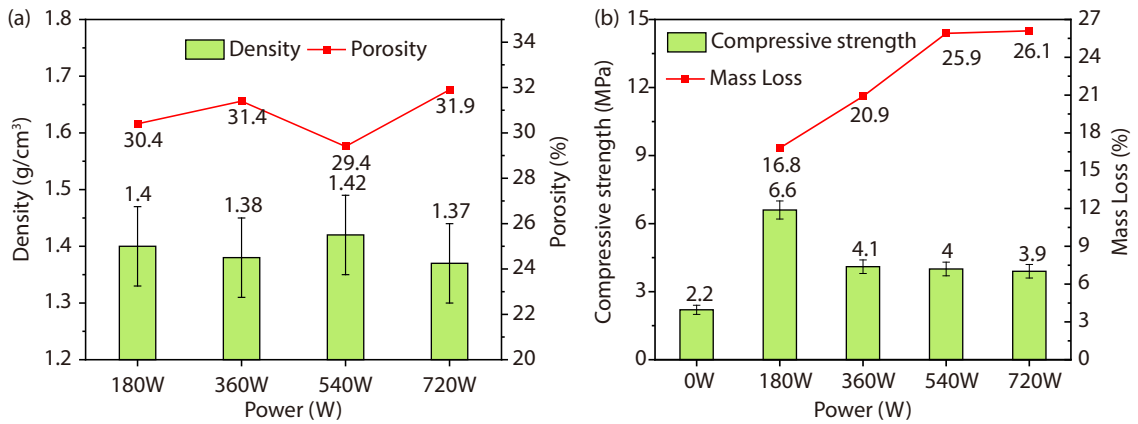

Fig. 4. The influence of microwave power on geopolymer: (a) porosity and density, (b) compressive strength. Reproduced with permission from Ref. [94].

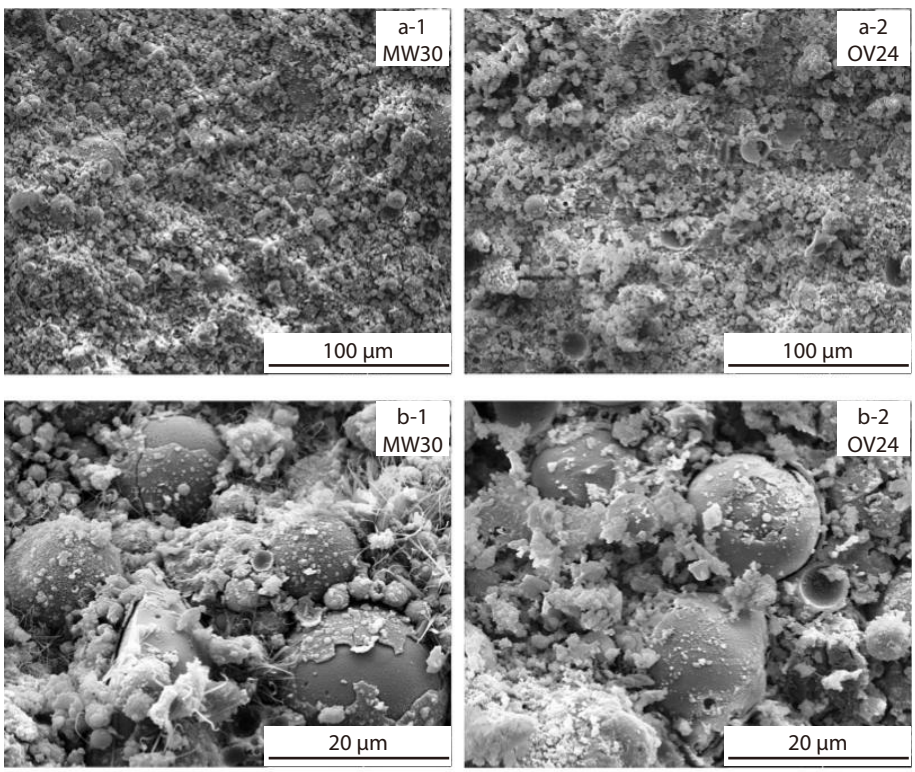

Fig. 5. Microscopic morphology of fly ash hydration paste. Reproduced with permission from Ref. [93].

matrix, which causes internal particles to generate heat through friction[97]. This process promotes depolymerization and polymerization reactions, thereby accelerating the overall polymerization kinetics. Microwaves can also excite polar molecules to higher energy states, facilitating internal chemical reactions. Currently, research on microwave curing is primarily focused on experimental investigations and practical applications aimed at accelerating the setting and hardening of concrete and cementitious materials[98-100]. In the field of alkali activation, microwave curing is primarily applied to fly ash-based geopolymer systems[87]. The presence of hollow glass microspheres in fly ash facilitates microwave penetration, enabling rapid and uniform hardening[87]. Gultekin et al. found that, compared with HTC, microwave curing allows for faster preparation of fly ash-based geopolymer[101]; however, the improvement in strength is limited. This limitation arises because microwaves are more effective at accelerating the setting of the slurry, while the rapid evaporation of water hinders the achievement of optimal densification. Further research is still required to explore microwave curing of geopolymers in other alkali-activated systems.

2.5. Vacuum curing

Vacuum curing (VC) refers to the process of placing geopolymer specimens in a low-pressure environment, where the reaction kinetics and transport processes are altered by reducing the system's gas pressure. Compared with conventional curing, the vacuum environment can significantly affect the internal gas phase behavior, water migration, and distribution of reactants in the slurry, thereby influencing the microstructural formation and the development of macroscopic properties in geopolymer[102].

Systematic research on VC in the field of geopolymer remains limited. Existing studies primarily focus on the macroscopic effects of a vacuum environment on the performance of traditional cementitious systems[103], such as ordinary Portland cement, including its influence on the types of hydration products[104], pore structure characteristics, and early strength development[105]. Although these studies have partially elucidated the regulatory mechanisms of low-pressure environments on water migration, bubble release, and reaction kinetics in cementitious materials, thereby providing valuable insights into the fundamental role of vacuum treatment, there remains a lack of in-depth analysis regarding the coupling relationship between reaction, microstructure, and performance in alkali-activated geopolymer systems under VC.

The duration of exposure to a vacuum environment significantly influences the hydration products of hardened cement paste, with the calcium sulfoaluminate system exhibiting greater sensitivity under high vacuum conditions. Cullingford et al. observed that VC enhanced the compressive strength of concrete, although it also resulted in pore coarsening[106]; in contrast, Namba et al. reported opposing results[107]. Current research indicates that a vacuum environment can effectively facilitate the release of entrapped air in fresh geopolymer paste. Davis et al. pointed out that under negative pressure conditions, bubbles entrapped within the matrix can be effectively removed, leading to a significant reduction in total porosity, improved pore structure parameters, and enhanced mechanical properties (as shown in Fig. 6)[31]. Zhou et al. obtained similar findings in their study on metakaolin-based geopolymer. Furthermore, a vacuum environment can accelerate the evaporation and migration of free water, which to some extent promotes the dissolution and reorganization of silicate and aluminate species[108]. However, as the geopolymerization reaction is not solely dependent on hydration, excessive water loss may result in an insufficient reaction medium, thereby inhibiting the polymerization process.

It is noteworthy that VC has a relatively limited effect on the overall phase composition of the reaction products. Duxson et al., through XRD analysis, indicated that vacuum treatment does not alter the main phase composition of the amorphous geopolymer gel phase, although it may influence its short-range ordered structure and the cross-linking degree of the N-A-S-H gel[109]. As presented in Table 4, XRD studies on various cementitious materials under vacuum conditions further support the notion that vacuum treatment primarily affects structural evolution rather than inducing the forma-

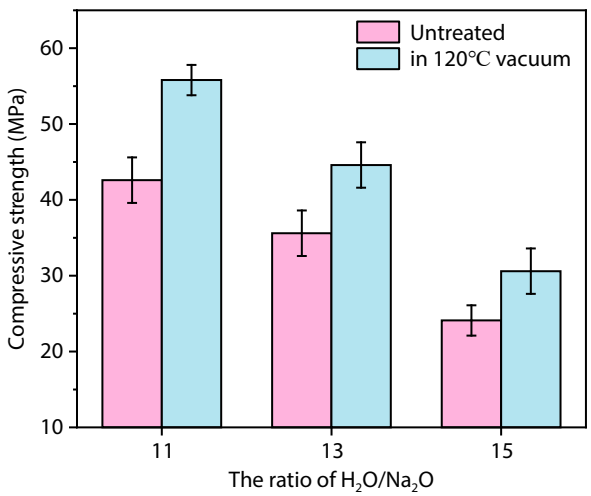

Fig. 6. Changes of compressive strength of geopolymer under different conditions. Reproduced with permission from Ref. [31].

Table 4. The effect of varying vacuum conditions on the XRD patterns of hardened cement paste.

Cement	Curing condition	Vacuum condition	XRD result	Ref.
OPC, SAC	20 °C, RH≥95%, 2 d	RT, (100±10) Pa	No difference, $CaCO_3$ and C_2S increased	[31]
CSA	25 °C, 30 d	RT, 4 Pa, 7 d	AFt reduced, AFt destroyed	[110]
	85 °C, 30 d	RT, 4 Pa, 7 d	AFt and AFm destroyed	
OPC	20 °C, 7 d	RT, 1 Pa, 7 d	Amorphous appeared, transformed to $10 \cdot H_2O$ AFm	[111]
OPC	20 °C, RH≥95%, 7 d	RT, (2000±200) Pa, 7 d	No difference	[112]

tion of new phases.

Although VC demonstrates significant potential in optimizing pore structure and enhancing early-stage strength, it still encounters various challenges in practical applications[14,31]. A complex coupling relationship exists among vacuum degree, treatment duration, and material composition. Moreover, the negative pressure environment may accelerate water evaporation, which can adversely affect the continuity of the reaction, particularly in systems with a low liquid-to-solid ratio or under high-temperature conditions. The key to maintaining favorable mechanical properties of cementitious materials in a vacuum environment depends on whether sufficient time is available to ensure early hydration and support subsequent strength development[113]. Although research on VC began at an early stage, findings were inconsistent, and progress was interrupted due to a lack of practical application scenarios. With the emergence of concepts such as "high-speed trains"[114], there is a renewed need to further expand performance-related research on VC.

2.6. Steam curing

Steam curing serves as a milder alternative to autoclave curing, utilizing saturated steam at atmospheric or near-atmospheric pressure to heat and humidify geopolymer specimens, thereby effectively promoting early-stage reactions. Within the optimal temperature range of 60–80 °C, the dissolution of aluminosilicate precursors is significantly accelerated, and early gel phases such as N-A-S-H rapidly form, effectively shortening the reaction induction period[115]. However, while sustained high-temperature and high-humidity conditions help maintain the reaction medium, they may also lead to the leaching of soluble alkali components, alter the alkalinity of the liquid phase, and induce local reorganization or coarsening of the gel structure. These effects can ultimately hinder the further progression of later-stage reactions and the development of a refined, dense microstructure[44].

Numerous studies have demonstrated that steam curing is particularly advantageous for enhancing the performance of geopolymers synthesized from low-calcium aluminosilicate raw materials, such as fly ash and slag. Qian et al. systematically examined the effects of steam curing on both the microstructure and macroscopic properties of geopolymers and found that suitable steam curing conditions (60–80 °C) can significantly improve compressive and flexural strengths, reduce total porosity, and enhance impermeability[116]. This effect is attributed to the fact that the steam environment promotes the early formation of the gel phase and strengthens the interparticle bonding, resulting in a more uniform and compact microstructure. Lu et al. further noted that although steam curing can effectively shorten the formation time of materials, the thermal and humid conditions introduced by steam may also lead to pore structure coarsening, which could negatively affect the material's electrical conductivity and piezoelectric properties[33]. Therefore, in functional applications, curing parameters should be carefully optimized.

Parameter control in steam curing is of critical importance. The curing temperature is typically recommended to be maintained between 60 °C and 80 °C[43]. Temperatures exceeding 90 °C or prolonged exposure may easily induce micro-crack formation due to concentrated thermal stress and the spatial inhomogeneity of the hydration reaction. In low-pressure environments, such as those at high altitudes, a low-temperature steam curing regime of 40 °C to 60 °C is recommended to minimize the risk of thermal damage. Furthermore, Ma et al.'s research indicates that steam curing also significantly influences the long-term volume stability of geopolymers[117]. The difference in the 90-day dry shrinkage rate between steam-cured and non-steam-cured specimens can reach up to 25.30%, highlighting the positive role of this curing method in mitigating shrinkage.

Despite its advantages, steam curing also has certain limitations. Prolonged exposure to high temperature and humidity can cause leaching of soluble alkali components in geopolymers, leading to surface powdering and weakening of the interfacial transition zone[118]. Although the sustained thermal and humid conditions accelerate early gelation, they may also induce microcrack accumulation in the interface transition zone, thereby hindering the continued development of later-stage strength[119,120]. Therefore, steam curing is more appropriate for prefabricated non-structural elements or temporary applications where early strength is prioritized over long-term durability.

2.7. Internal curing

Internal curing (IC) technology, originally developed for high-performance concrete, has been increasingly applied to geopolymer systems in recent years. This approach introduces internal water reservoirs to offset water consumption and evaporation during reaction, thereby improving moisture distribution and mitigating autogenous shrinkage and microcracking[45]. Typical IC agents include superabsorbent polymers (SAP)[121], pre-saturated lightweight aggregates[122], porous ceramic microspheres, and water-absorbing fibers[123]. These materials absorb water during mixing and release it gradually during curing, extending the reaction period and facilitating the spatial development of the binding phase.

The benefits of IC in geopolymers have been clearly demonstrated. As early as 1999, Collins et al.[124] incorporated saturated blast furnace slag aggregates into geopolymers, observing significant reductions in drying shrinkage along with improved compressive strength. Subsequent studies confirmed that SAP or pre-saturated aggregates effectively reduce autogenous shrinkage, enhance dimensional stability, and improve crack resistance[125]. The mechanism operates on two levels: first, by supplying internal moisture during critical gel network formation, it promotes more complete hydration; second, the gradual water release mitigates capillary tension, thereby restraining shrinkage and stress accumulation[126]. However, current research remains predominantly focused on alkali-activated slag systems[127-129], with limited attention to other geopolymer types.

The broader implementation of IC in geopolymers still faces several challenges. Different alkali-activated systems (e.g., Na^+- vs. K^+-based) respond differently to the release kinetics of curing agents, requiring system-specific optimization[130]. The dosage, particle size, and distribution of these

agents strongly influence water release behavior and resultant performance, underscoring the need for compatibility criteria aligned with geopolymerization kinetics. Moreover, the incorporation of IC agents may introduce interfacial zones or macro-defects, potentially compromising mechanical properties.

Notably, the efficacy of IC agents varies considerably with raw material composition. Low-calcium systems (e.g., metakaolin-based geopolymers), with their slower reaction rates, depend heavily on sustained moisture supply and may benefit from high-retention agents such as specific-sized SAP or pre-saturated porous ceramics. In contrast, high-calcium systems (e.g., slag or high-calcium fly ash-based geopolymers), given their higher reactivity, are more sensitive to the timing and rate of water release. Therefore, future work should systematically evaluate the effects of IC agent type, size, dosage, and release dynamics on reaction progress and microstructure across different geopolymer systems to enable precise performance control.

To advance this technology from fundamental understanding to practical application, future research should prioritize the development of tailored IC materials, clarify the coupling between water release behavior and reaction pathways, and employ multi-scale characterization to elucidate the impact of IC on microstructural evolution and long-term performance.

2.8. Water bath curing

Water bath curing (WBC) is a mild thermal treatment method for geopolymer specimens conducted in a constant-temperature water bath environment. This method involves complete immersion of the specimens in hot water (typically at 40–90 °C), allowing reactions to proceed under stable hygrothermal conditions. Compared to ambient curing, the continuous and gentle heating provided by the water bath effectively promotes the dissolution of aluminosilicate precursors and subsequent polycondensation, thereby optimizing the reaction process[131].

In alkali-activated material systems, WBC is widely employed to facilitate the formation of zeolite-like phases. Research indicates that under suitable temperatures (e.g., 60–80 °C) and alkaline conditions, WBC not only aids in the formation of amorphous N-A-S-H gel but also induces its gradual transformation into crystalline zeolitic phases such as sodalite and chabazite[132]. This "gel-to-crystal" transition enables the material to retain certain mechanical properties while also exhibiting functional characteristics typical of zeolites, such as adsorption, ion exchange, and catalytic capabilities (as shown in Table 5).

Compared to traditional zeolite synthesis processes, zeolite formation via geopolymer conversion offers the advantage of lower energy consumption, with crystallization occurring over a broad temperature range (25–150 °C) and without the emission of harmful gases such as CO_x or SO_x. Liu et al. successfully prepared a geopolymer-based zeolite composite membrane using a low-temperature water bath method; the material demonstrated excellent acid resistance and regeneration performance, maintaining 95% removal efficiency after multiple cycles with $NaHCO_3$[137]. Baykara et al. further investigated the environmental impact of zeolite and phosphoric acid-modified geopolymers, finding that higher water bath temperatures and lower phosphoric acid concentrations positively influenced compressive strength[138]. Wang's team synthesized a novel geopolymer-zeolite composite via WBC, which not only maintained good compressive strength but also exhibited an adsorption capacity 3.27 times that of conventional zeolites, indicating superior specific surface area and pore structure[134].

In summary, WBC holds significant importance in the laboratory preparation of geopolymer-based zeolite composites, adsorbent carriers, and environmental functional materials. Although the method is simple and mild, the reaction pathways and final structures are highly dependent on parameters such as curing temperature, alkali concentration, solid-to-liquid ratio, and raw material composition. Future work should focus on systematic and in-depth research into phase evolution mechanisms and the integrated design of structure-function relationships.

3. Multi-field coupling composite curing method

With the continuous enhancement of performance requirements for geopolymer, the limitations of single physical field curing have gradually become evident, making it challenging to simultaneously achieve multiple objectives such as early strength development, high density, low defect content, and superior durability. Multi-field coupling composite curing technology, by synergistically regulating two or more physical fields, integrates the advantages of different curing mechanisms while compensating for the shortcomings of individual methods, thereby emerging as a key approach to overcoming the performance bottlenecks of geopolymers. This section focuses on the principles, implementation processes, and synergistic enhancement mechanisms of typical composite curing techniques—such as autoclave curing (thermal-hygro-pressurization coupling)[139], hot-pressing curing (thermal-pressurization coupling)[140], and synchronous vacuum hot-pressing curing (thermal-vacuum-pressurization coupling)[141]—in relation to the geopolymerization reaction, microstructure evolution, and final mechanical properties, as shown in Table 6. By analyzing the reaction kinetics, struc-

Table 5. Comparison of the adsorption properties of different polymers and zeolites.

Raw materials for geopolymers	Adsorption condition	Adsorption capacity (mmol g^{-1})	Ref.
Metakaolin/Silica fume	35 °C, 0–1 atm	0.2–0.36	[133]
Coal fly ash	25 °C, 1 atm	0.69–2.06	[134]
Coal fly ash/Rice husk ash/Kaolinite	35 °C, 1 bar	0.63–0.8	[135]
Geopolymer-zeolite	35 °C, 0–1 bar	0.50–1.90	[136]

Table 6. Comparative analysis of composite curing methods.

Curing method	Core principle	Energy consumption and early-age strength	Applicable scenarios	Limitations	Ref
Autoclave curing	High-temperature & pressure steam enhances crystallization	High/Significant	Lightweight aggregates, HPC components	High energy cost, complex equipment, pore coarsening risk	[19]
Hot-pressing curing	Synergistic heat & pressure for densification	Medium-High/High	Precast elements, high-strength boards	Specialized equipment, complex parameter control	[140]
Synchronous vacuum hot-pressing curing	Multi-field coupling (heat-pressure-vacuum) for ultrafast polymerization	High/Exceptional	UHPC, high-temperature components	Complex setup, lab-stage	[35]

tural formation characteristics, and performance enhancement effects under multi-physical field environments, this work provides a scientific basis and technical pathways for the development of high-performance, low-energy-consumption, and engineering-feasible novel geopolymer curing processes.

3.1. Autoclave Curing

Autoclave curing accelerates the hardening process and enhances the strength development of test blocks through the application of steam pressure. A typical autoclave curing cycle is illustrated in Fig. 7. The high-temperature and high-humidity conditions within the autoclave promote hydration reactions, thereby accelerating the setting and hardening of geopolymer, reducing curing time, and improving early strength and durability. Currently, this technique is widely employed in the production of autoclaved aerated concrete blocks and lightweight aggregates[142-144].

The mix proportion design, temperature, pressure, pre-curing duration, and curing time all influence the development of material performance[139,145]. Among these factors, temperature and steam pressure are the key parameters in autoclave curing. Yazıcı et al. reported that the compressive strength of autoclave-cured concrete can exceed 200 MPa[146]. Although increasing the steam temperature and pressure can enhance the crystallinity of the matrix and thereby improve strength, it may also result in a slight reduction in mechanical properties (as shown in Fig. 8). Singh et al. investigated a fly ash-based geopolymer incorporating varying dosages of limestone and quantitatively analyzed the effects of temperature and steam pressure (as shown in Fig. 9)[27]. Their results indicated that increasing both the curing temperature and steam pressure contributes to enhancing material performance, with the influence of steam pressure being more significant compared to water bath curing.

Autoclave curing exerts a significant influence on the mechanical properties of fly ash-based geopolymers[139,145]. Chen et al. conducted a systematic investigation into the variations in compressive strength of geopolymers with different fly ash contents under autoclave curing conditions. The results showed that the compressive strength of the autoclave-cured samples on the structural surface was markedly higher than that of the standard-cured group, with the maximum increase reaching 37.5%. The optimal pressure value increases with rising fly ash content, indicating that higher pressure is more appropriate for geopolymers with a high fly ash content, which is particularly beneficial for fly ash-based products. However, it should be noted that when the autoclaving time exceeds 10 h, a strength reduction of 5%–10% occurs, and the magnitude of this decrease becomes more pro-

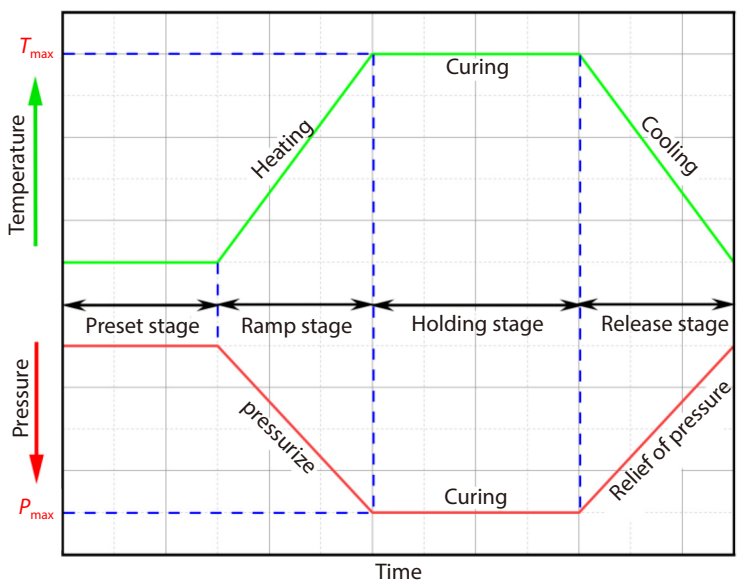

Fig. 7. Schematic diagram of autoclave curing.

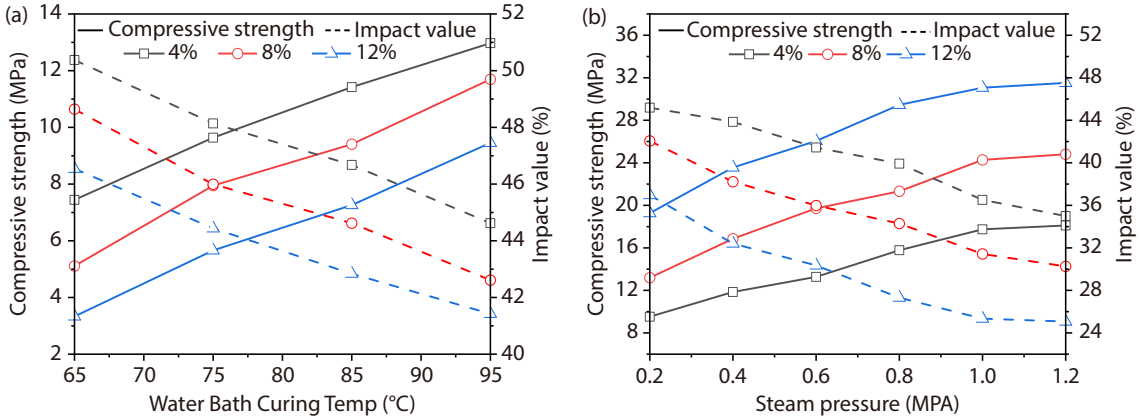

Fig. 8. Compressive strength of geopolymers at different temperatures and steam pressures: (a) water bath curing temperature; (b) steam pressure. Reproduced with permission from Ref. [27].

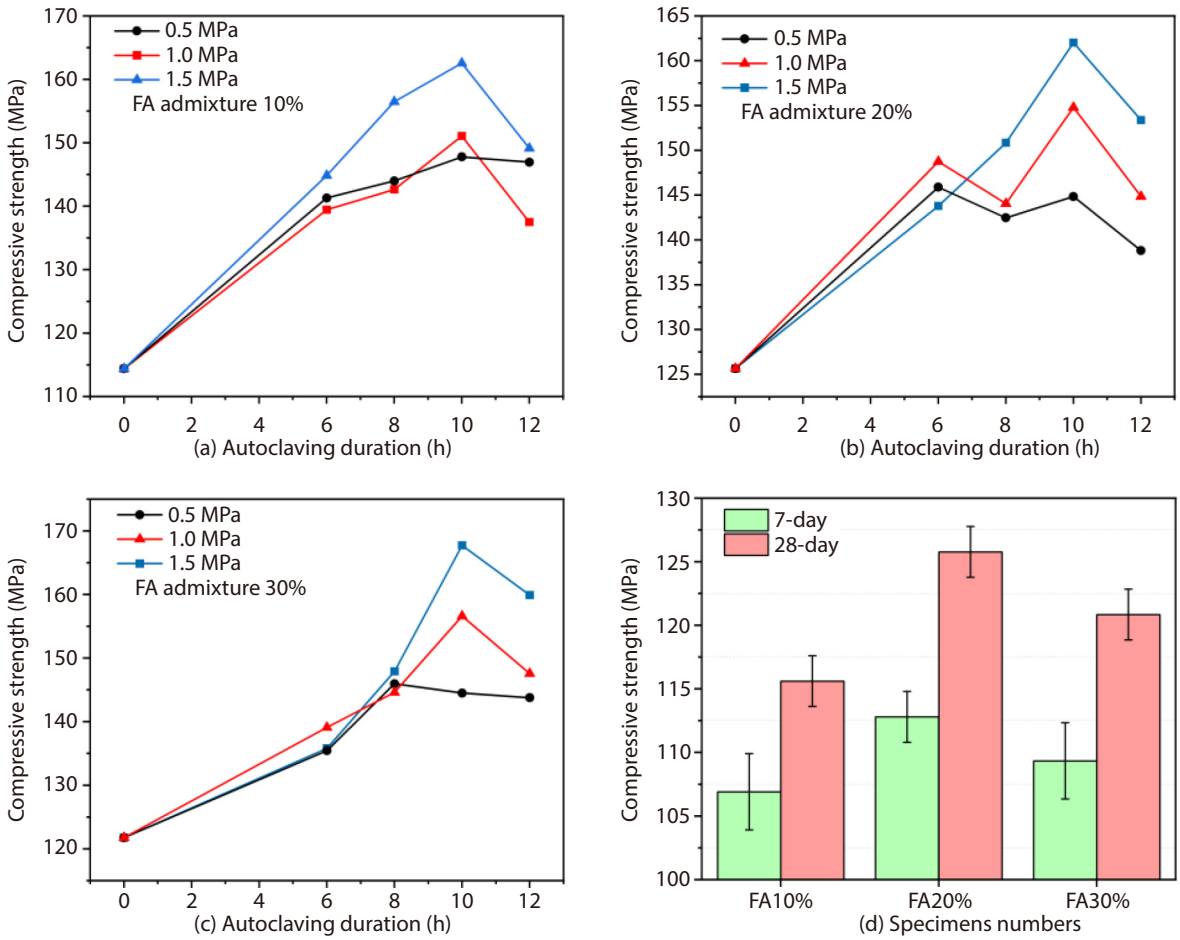

Fig. 9. Compressive strength of UHPC after standard curing and autoclave curing. Reproduced with permission from Ref. [147].

nounced at higher pressure levels.

Autoclave curing can significantly shorten the curing period of geopolymer[148]. The high-temperature and high-humidity environment accelerates hydration reactions, enhances mechanical properties, reduces pore content and microcrack formation, and improves both compactness and durability[149]. However, this curing method requires sustained high temperature and humidity, which leads to high energy consumption and increases construction complexity and production costs.

3.2. Hot pressing curing

Hot-pressing curing (HPC) is a process conducted under elevated temperature and pressure, similar to the compression molding technique used in composite materials. It is widely applied in fields such as cement-based composites[147], recycled concrete[150], and glass ceramics[151]. For geopolymers, hot-pressing accelerates the reaction of aluminosilicates, leading to the formation of a dense matrix. This method not only

reduces both the size and volume of pores but also transforms the continuous pore network into a closed structure. Research has demonstrated that metakaolin-based geopolymers can expel most of the entrapped air under a pressure of 4 MPa, thereby significantly enhancing early compressive strength[8].

During the hot pressing process, the dissolution, depolymerization, and repolymerization of aluminosilicates occur nearly simultaneously, as illustrated in Fig. 10. During the molding stage, the matrix temperature rises, system pressure increases, and the viscosity of the liquid phase decreases, which facilitates the rapid and uniform distribution of the alkali activator[152]. Silicate and aluminate monomers are released from the matrix. As the temperature continues to rise, the reaction rate increases markedly[153].

Research by Ranjbar et al. and Provis et al. on hot-pressed fly ash-based geopolymer revealed that temperatures exceeding 200 °C lead to continuous water evaporation, with nearly all free water being released[154,155]. Sustained pressure application promotes the conversion of solid particles into geopolymer gel, while low-molecular-weight polymers form through dissolved species, ultimately resulting in the formation of N-A-S-H gel. The three-dimensional silicoaluminate gel network drives the system toward thermodynamic stability. After cooling, an amorphous to semi-crystalline geopolymer is formed, exhibiting high load-bearing capacity. Cao et al. investigated the feasibility of fabricating strain-hardening fly ash geopolymer composite boards (FA-SHGC) through hot pressing[32]. Their results showed that the 7-day compressive strength of untreated FA-SHGC reached 10 MPa, and under hot-pressing conditions of 80 °C and 3.2 MPa, the strength increased by 2.5 times. Furthermore, the hot-pressed SHGC demonstrated excellent multiple cracking and strain-hardening behavior.

The physical and chemical properties of geopolymer undergo significant changes after being subjected to hot pressing for 30 min. The increase in system pressure accelerates water evaporation, with some liquid being expelled, leading to a reduction in sample mass. This indicates that the majority of water in the geopolymer exists as free water[156]. The volume change of the hot-pressed geopolymer is influenced by the applied pressure, while its density is governed by both porosity and water content, with pressure serving as the dominant factor. Compressive strength ranges from 29.0 to 160.0 MPa and shows a positive correlation with both temperature and pressure (as illustrated in Fig. 11d). The stress distribution within the dense matrix is uniform, which mitigates stress concentration in porous regions and delays crack formation[157].

Hot-pressing curing enables the rapid fabrication of high-strength geopolymer with minimal usage of alkali activator and water, while promoting a more uniform distribution of these components under pressure. The early mechanical properties of hot-pressed geopolymer are excellent, and unreacted particles can continue to participate in reactions, further enhancing strength in later stages. The rapid formation of an early gel and the subsequent development of high strength demonstrate the significant potential of hot-pressing curing in geopolymer applications, particularly for the production of prefabricated components.

3.3. Synchronous vacuum hot-pressing curing

Synchronous vacuum hot-pressing (SVHP) curing is an innovative composite curing technology that integrates high temperature, mechanical pressure, and a vacuum environment[141]. By coupling multiple physical fields, this method effectively combines the advantages of individual hot-pressing, vacuum, and high-temperature curing techniques, while mitigating their respective limitations. It offers a novel approach for the fabrication of high-performance geopolymer with precisely controllable microstructures.

During the SVHP curing process, three physical conditions work synergistically: the high-temperature environ-

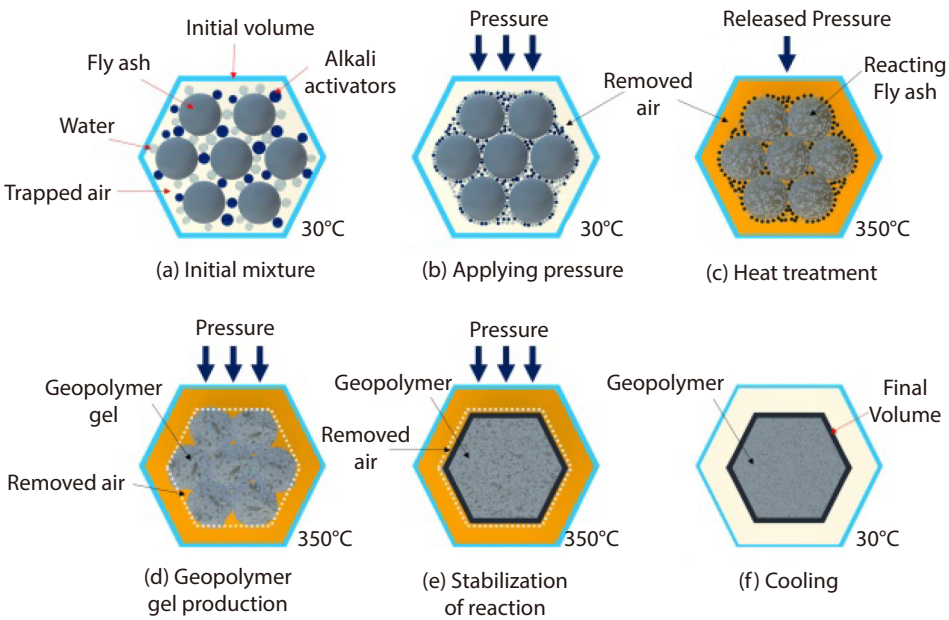

Fig. 10. The polymerization mechanism of hot-pressed geopolymer. Reproduced with permission from Ref. [154].

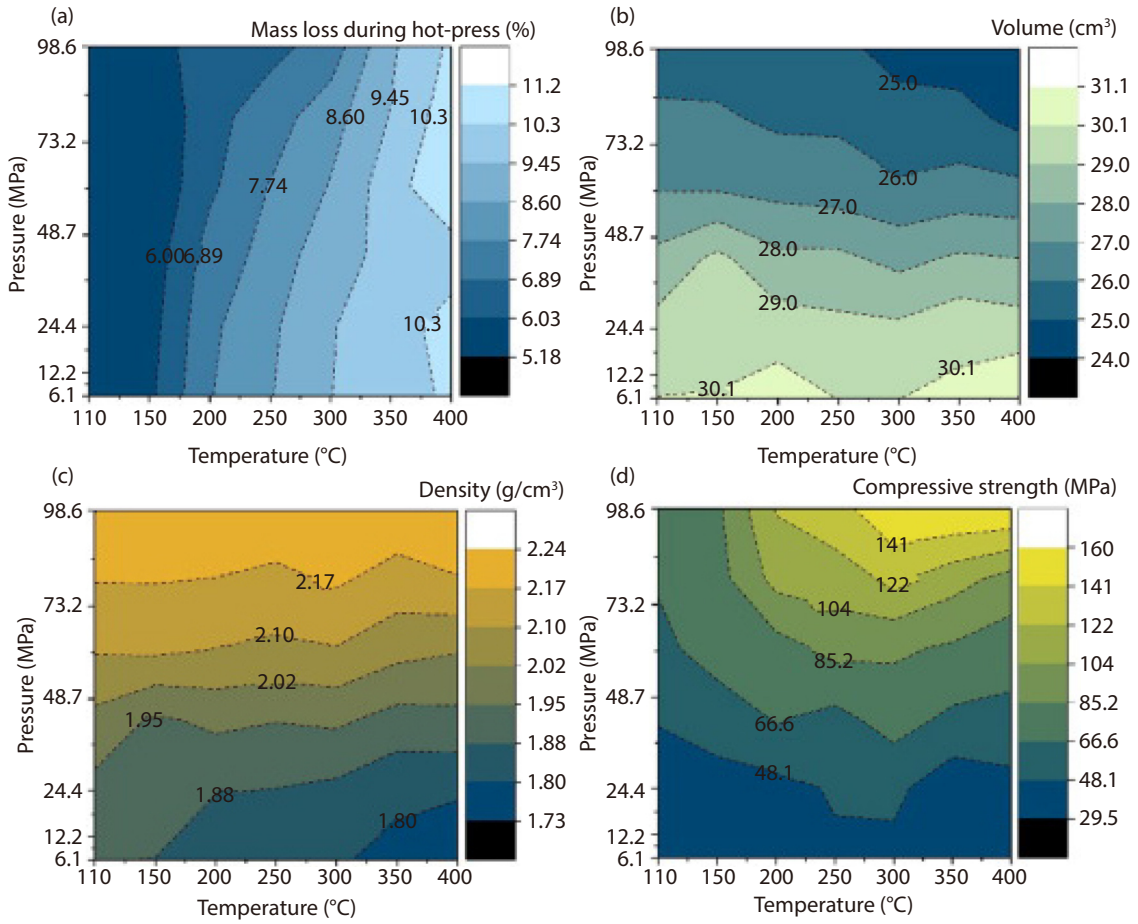

Fig. 11. Hot-pressed geopolymer: (a) mass loss, (b) volume, (c) density, (d) compressive strength. Reproduced with permission from Ref. [16].

ment (typically ranging from 80 °C to 200 °C) significantly accelerates the dissolution and depolymerization of aluminosilicate precursors, promoting the rapid formation of the gel phase[158]; mechanical pressure (commonly in the range of 2–10 MPa) facilitates particle rearrangement, reduces porosity, and expels entrapped air and excess moisture, thereby greatly improving the material's density[159]; and the vacuum environment effectively eliminates bubbles, suppresses pore formation, and enhances the uniform distribution of alkali activators and water within the slurry, preventing localized drying or uneven reactions[14]. The combined action of these three factors markedly improves the reaction kinetics and microstructural development of the geopolymer.

Yang et al. successfully fabricated an ultra-high-performance ceramic-like geopolymer with a compressive strength of up to 90.92 MPa within an extremely short curing period of 30 min using this technique[141]. The material also demonstrates excellent high-temperature resistance, capable of withstanding temperatures as high as 1200 °C, along with superior volume stability and durability[35]. The underlying reason for this significant performance enhancement is the synergistic effect of high temperature, high pressure, and vacuum conditions, which accelerate the polymerization reaction and lead to the formation of a unique "ceramic-like" microstructure.

A large number of "intermediate phase" structures, existing between the amorphous gel and crystalline phases, were formed in the geopolymer matrix treated by SVHP (Fig. 12a). These intermediate phases serve a critical bridging function within the system, effectively connecting the more ductile gel regions with the higher-strength crystalline regions, thereby optimizing the stress transfer pathway (Fig. 12b). Under external loading, such structural features can delay the initiation and propagation of microcracks, significantly improving the material's toughness and crack resistance, and addressing the common issue of brittle fracture in traditional geopolymers[160]. Furthermore, this dense and continuous microstructure also effectively hinders the penetration and migration of oxygen and volatile species at elevated temperatures, endowing the material with excellent high-temperature stability and anti-sintering capability (Fig. 12c, d).

The SVHP technology has facilitated the transformation of geopolymer from a brittle gel into a toughened ceramic composite material, offering a novel direction for its application in ultra-high-performance building materials, advanced structural ceramic substitutes, and high-temperature protective components. Currently, this technology remains at the laboratory research stage and faces several challenges, including complex equipment requirements, high production costs, and the intricate coupling of process parameters. Future research should focus on exploring its feasibility for large-scale manufacturing, establishing a comprehensive "process-structure-property" control framework, and advancing its practical implementation in engineering applications.

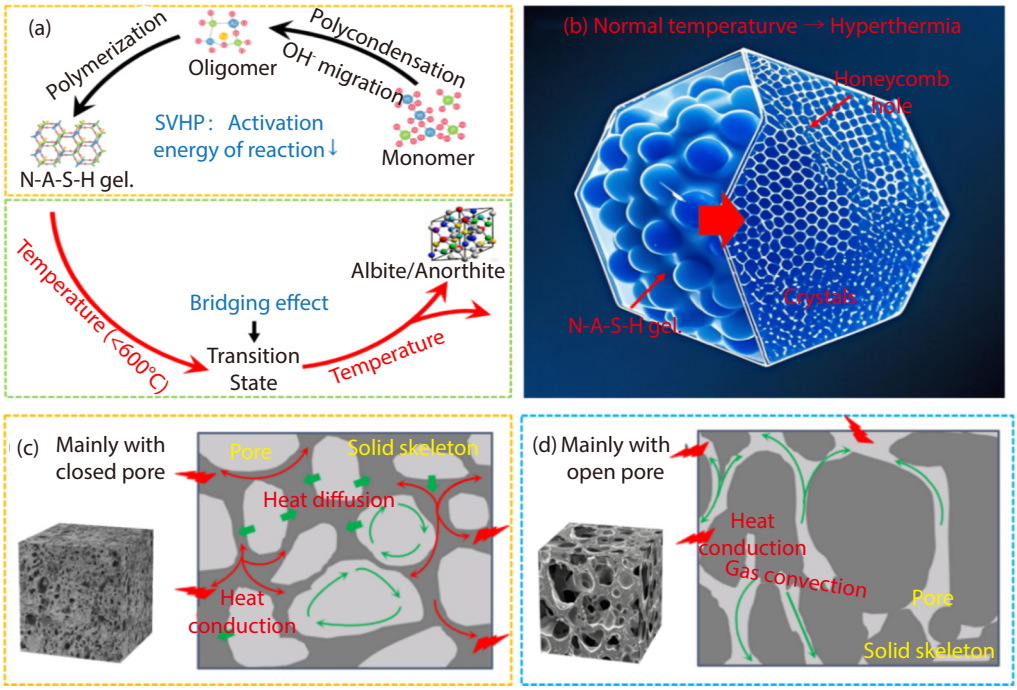

Fig. 12. Synchronous vacuum hot-pressed geopolymers: (a) rapid polymerization mechanism; (b) product transformation at high temperatures; (c, d) transformation of pore structure. Reproduced with permission from Ref [35].

4. Discussion

While significant progress has been made in understanding geopolymer reaction mechanisms and optimizing material design—particularly concerning activator chemistry, raw material compatibility, and macroscopic performance—research on curing regimes remains relatively fragmented. Most studies focus on individual curing parameters, whereas the polymerization kinetics and microstructural evolution under multi-physical-field coupling are still poorly understood[161-163]. This knowledge gap is especially pronounced under extreme or combined conditions such as high temperature, pressure, and vacuum, where the mechanisms governing early-age structural formation, long-term performance evolution, and damage initiation have not been systematically elucidated. This limits the reliable and predictable fabrication of high-performance geopolymer components for demanding applications.

A deep understanding of how curing conditions dictate the polymerization pathways and microstructural architecture of geopolymers remains a critical yet underexplored area. This review systematically bridges this gap by synthesizing the mechanistic influences of various curing methods. Elevated temperature, as a universal accelerator, primarily provides the kinetic energy necessary to overcome the activation barriers for the dissolution of aluminosilicate precursors and the subsequent polycondensation reactions, often leading to a more cross-linked but potentially coarsened pore structure if uncontrolled[164]. In contrast, applied pressure exerts a physical influence by promoting particle rearrangement and expelling entrapped air and excess water, thereby directly enhancing microstructural density and reducing capillary porosity, without fundamentally altering the chemical reaction pathway[165,166]. The vacuum environment uniquely impacts the reaction by removing air barriers for ion migration and facilitating the uniform distribution of the alkaline activator, while its tendency to accelerate water evaporation can truncate the polymerization process if not properly managed[167]. Electric field curing introduces a non-thermal effect through ion migration in addition to Joule heating, potentially aligning the reaction products and modifying the gel morphology[168]. The most profound effects are observed under multi-field coupling, such as in SVHP curing, where the synergistic application of heat, pressure, and vacuum not only accelerates reaction kinetics but also can induce the formation of unique intermediate phases that bridge the amorphous gel and crystalline domains, creating a toughened ceramic-like microstructure. Therefore, the choice of curing method is not merely a matter of process acceleration but a fundamental tool for steering the reaction trajectory and tailoring the final material's properties.

The future of geopolymer curing does not lie in reliance on individual methods, but in the intelligent integration of these physical fields to generate synergistic effects. Multi-field coupled curing technology represents a key direction for overcoming the performance bottlenecks of geopolymers. Through coordinated control strategies such as thermal-pressure-vacuum and electric-thermal-vacuum, it is possible not only to leverage the advantages of each environmental parameter but also to compensate for the limitations of their individual applications. This approach optimizes reaction kinetics, enables precise design of the microstructure, and significantly enhances material properties. For instance, synchronous vacuum hot-pressing curing has demonstrated considerable potential in producing ultra-high-performance geopolymers, confirming that multi-field coupling can induce the formation of a "gel-crystal bridging" transition phase,

thereby substantially improving both the material's toughness and high-temperature stability. Future research should focus on elucidating the structural formation mechanisms, interfacial evolution behaviors, and large-component molding processes under composite curing conditions. Establishing a "curing-structure-property" mapping model will be essential to advance the industrial application of geopolymers in areas such as prefabricated low-carbon building materials and high-temperature resistant components.

Current research primarily focuses on the enhancement of early strength and microstructure in geopolymers through rapid curing, while its long-term effects require systematic evaluation. Studies indicate that methods like high-temperature and steam curing, while improving early strength, can hinder later strength development or even cause strength regression due to rapid water evaporation or thermal stress. Furthermore, the impact of rapid curing on durability indicators such as carbonation, freeze-thaw, and chemical resistance remains unclear. Future work should prioritize long-term tracking (e.g., 90-day strength, drying shrinkage, carbonation depth, chloride permeability) under various curing regimes to establish the relationship between the curing regime and long-term performance and build a comprehensive framework for property control from early-age enhancement to long-term durability.

The practical viability and industrial potential of these advanced curing strategies are already being validated in real-world applications. The advantages and synergistic effects of rapid curing methods are demonstrating tangible benefits beyond the laboratory. For instance, in the building materials sector, Conch Cement has extensively adopted steam curing processes in the production of precast concrete components. This practice significantly enhances early strength development and production efficiency, providing crucial technical support for large-scale projects such as high-speed rail and prefabricated construction. On another front, in energy engineering, Shell's "Mud to Cement" technology relies fundamentally on rapid solidification processes to convert drilling waste into a hardened cementitious material for wellbore sealing within a short timeframe. This application showcases the potential of geopolymerization and rapid curing technologies for waste valorization and operational efficiency in challenging downhole environments. These cross-industrial cases underscore that advanced curing technologies, rooted in a fundamental understanding of reaction mechanisms, are not only theoretically superior but also robustly applicable and economically beneficial in practice. They provide a compelling rationale and a solid foundation for the broader industrial adoption of geopolymers, bridging the gap between laboratory research and full-scale engineering practice.

5. Conclusion and outlook

Geopolymer, as an eco-friendly and tunable cementitious material, holds significant potential for advancing green and low-carbon transformation in construction. This review systematically examines how curing methods regulate geopolymer mechanical properties and microstructure, underscoring curing as a critical factor in reaction behavior and final performance. While optimization of individual curing conditions has improved early strength, most rapid curing techniques still face challenges such as high energy consumption, complex procedures, and uncertain long-term performance, limiting their engineering application. Future research should transition from "single-parameter regulation" to "multi-field collaborative design", focusing on:

(1) Strengthening fundamental research on multi-physics coupling curing to elucidate polymerization kinetics, phase evolution, and microstructure formation under complex conditions, establishing cross-scale "curing-structure-performance" models;

(2) Coordinated optimization of material design and curing processes, investigating adaptability of raw material systems (e.g., fly ash, slag, metakaolin) and their parameters (e.g., Si/Al ratio, alkali content) to composite curing methods, while addressing strength regression and durability issues;

(3) Advancing intelligent and sustainable curing processes by developing energy-efficient, rapid technologies compatible with industrial prefabrication or on-site construction to enhance economic and environmental benefits;

(4) Fostering multidisciplinary innovation in materials, processes, and equipment to enable breakthrough applications of geopolymers in high-performance construction materials, advanced ceramics, and high-temperature components, thereby supporting the sustainable development of the materials industry.

Although rapid curing technologies can effectively enhance the early strength and microstructure of geopolymers, they still face several common challenges in practical engineering applications. Most rapid curing methods are energy-intensive, involve complex equipment, and incur high costs, making large-scale adoption difficult. The process parameters—such as temperature, pressure, and time—are highly coupled, and improper control can easily lead to defects such as pore coarsening and microcracking, thereby compromising long-term performance. Existing research predominantly focuses on early-age mechanical properties, with a lack of systematic evaluation of performance evolution under long-term service environments such as humidity, freeze-thaw cycles, and chemical erosion. Different raw material systems respond variably to curing conditions, and the limited adaptability of current processes restricts the synergistic utilization of multi-source solid wastes. Although composite technologies at the laboratory stage exhibit excellent performance, their engineering application is hindered by limitations in equipment scale and cost.

Future efforts should focus on developing low-energy, intelligent, and highly material-adaptive rapid curing processes, while strengthening long-term performance monitoring and standardization research to facilitate the transition of geopolymers from laboratory research to practical engineering applications.

Author contribution statement

Junchao Yang: Writing – original draft, Conceptualization,

Data curation, Investigation. **Peng Du**: Writing – review & editing, Supervision. **Xin Cheng**: Data curation. All the authors have approved the final manuscript.

Declaration of competing interest

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

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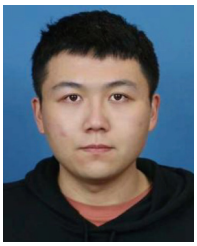

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