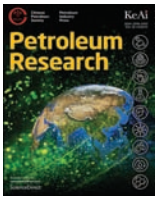
Petroleum Research 11 (2026) 274–296

Contents lists available at ScienceDirect

Petroleum Research

journal homepage: http://www.keaipublishing.com/en/journals/petroleum-research/



Review Article

A review on advancing clay-based geopolymers for high-temperature oil well cements: Mechanisms, durability, and applications



Barima Money [a], Rayan Hassan Modather [a], David Abutu [a], Norasyikin Ismail [a], Augustine Agi [a,b], Francis Nyah [a], Siti Qurratu' Aini Mahat [a,*]

[a] Faculty of Chemical and Process Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuhraya Persiaran Tun Khalil Yaakob Kuantan, Pahang, 26300, Malaysia
[b] Centre for Research in Advanced Fluid and Processes (Fluid Centre), Universiti Malaysia Pahang Al-Sultan Abdullah, Gambang, Pahang, 26300, Malaysia

ARTICLE INFO

Article history:
Received 10 February 2025
Received in revised form
18 August 2025
Accepted 18 August 2025
Available online 21 August 2025

Keywords:
Clay geopolymers
Reaction mechanisms
Oil well cement
Low carbon footprint
Geopolymerization

ABSTRACT

Geopolymers are promising alternatives to Portland cement due to their lower carbon footprint, superior mechanical strength, durability, and reduced shrinkage. However, inconsistent data and significant variations in experimental results highlight the uncertainty surrounding the reaction mechanisms of clay-based geopolymers (CBGs) in high-temperature oil wells. This review provides critical insights into these mechanisms and summarizes CBG synthesis methods. It explores the reaction processes of CBGs under high-temperature oil well conditions and analyzes the variables influencing these mechanisms. This review also examines the application of CBGs in oil wells, focusing on the challenges and potential solutions. Laboratory studies show that Portland cement degrades at temperatures above 300 °F (150 °C), while CBGs maintain their integrity and strength at temperatures up to 1500 °F (815 °C). This makes them particularly suitable for high-temperature geothermal wells and high-pressure, high-temperature oil well cementing. The dominant reaction mechanisms of CBGs include chemical reactivity, dissolution, gelation, polymerization, and growth. These findings highlight the potential of CBGs in addressing the challenges of high-temperature oil wells, thereby paving the way for further research in this area.

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1. Introduction

Good cementing is necessary for a successful oil well completion operation (Oseh et al., 2024; Temuujin, 2010). To minimize formation collapse, prevent corrosion from sulfate-rich formation waters, limit fluid movement across permeable zones, and preserve wellbore walls, oil well cementing is used as a mechanical support for the casing string (Bu et al., 2020; Kachoyan et al., 2022; Yahya et al., 2023, 2024a, 2024b). Ordinary Portland cement (class A–H) is designed specifically for oil and gas well cementing operations. However, the energy-intensive process of making Portland cement increases carbon dioxide (CO_2) emissions and contributes to global warming. In addition to these environmental concerns, Portland cement does not function satisfactorily in deep and ultradeep oil wells. For instance, Portland cement experiences strength retrogression at temperatures above 230 °F (Adjei, 2022; Nwaichi et al., 2024). Additionally, its low elasticity leads to sheath failure during perforation and hydraulic fracturing (Blkoor et al., 2021, 2022; Yan et al., 2024). These issues have spurred the search for alternative cement binders for oil well cement (Agi et al., 2023; Oseh et al., 2019).

Alkaline activated binders (geopolymers) show superior durability and mechanical strength, with reduced shrinkage compared to Portland cement, making them feasible lower-carbon alternatives. Geopolymers are created by combining concentrated alkaline hydroxide or alkaline silicate medium with aluminosilicate (Al_2SiO_5). Thereafter, the mixture is cured at room temperature or at 20°C-100 °C to initiate geopolymerization reaction. When the materials encounter an alkaline solution, the silicon [Si] and aluminum [Al] in them dissolve and form oligomers, which then undergo polycondensation to form calcium silicate [C–S–H], calcium aluminate hydrate [C-A-H], calcium Al_2SiO_5 hydrate [C-A-S-H], or sodium

* Corresponding author.
E-mail address: sitiqurratu@umpsa.edu.my (S.Q.A. Mahat).
Peer review under the responsibility of Editorial Office of Petroleum Research.

https://doi.org/10.1016/j.ptlrs.2025.08.005
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Al_2SiO_5 hydrate [N-A-S-H]. The use of Al_2SiO_5 materials, such as kaolin, fly ash, blast furnace slag, silica fumes, clay, calcium carbide residue, and dolomite, makes geopolymers environmentally friendly alternatives to Portland cement. Geopolymers have wide-scale applications in the construction industry, such as roads, bridges, and buildings; however, their applications in the oil and gas cementing industry remain limited. At present, researchers are investigating the behavior of various geopolymers under bottom-hole conditions in oil wells. For instance, Salehi et al. (2017) addressed the difficulty of brief thickening using a class F fly ash geopolymer. They reported that 5 h of thickening time is achievable, and the geopolymer cement shows higher compressive strength after 14 days of curing. It exhibits a gain in strength with time compared to Portland cement, in which time retrogression effects are observed. Similarly, Bernal et al. (2014) developed a novel class-F fly ash as a geopolymer, examining its suitability for oil well cementing applications as a Portland cement substitute. Their findings showed that, compared to Portland cement, geopolymers have better mechanical and rheological qualities. Furthermore, temperature settings were used for the initial testing of the geopolymers. Intended for low-to-moderate temperature conditions, these geopolymers may be negatively affected by an abrupt rise in temperature, which occurs in oil wells.

Clays are also source materials for geopolymerization, especially for high-temperature oil wells. However, clay requires calcination to be transformed into a reactive form. Calcinated kaolin (metakaolin) is mostly used for this purpose. For example, Adjei (2022) simulated the effects of elevated temperatures (163 °F and 248 °F) on the microstructure of metakaolin. Analytical analysis showed the presence of new crystalline phases, such as gobbinite and anorthite, when metakaolin was cured at 163 °F. They concluded that the presence of the crystalline phase has the potential to cause thermal stress, weaken the system, and ultimately affect its ability to effectively isolate formation and support the casing. By contrast, Patrick et al. (2024) reported that metakaolin shows high compressive strengths of 35.94 ± 0.93 and 33.71 ± 0.37 MPa after 28 days of curing in brine baths (40 g/L NaCl and 40 g/L Na_2SO_4) at 70 °C and 90 °C, respectively. The clay-based geopolymer (CBG) paste has 70.73% amorphous phases, as observed in X-ray diffraction results, suggesting the presence of irregular and nonrepeating atomic structures. The findings of the atomic force microscope (AFM) analysis further demonstrated that the geopolymer pastes are free of cracks and contain few pores, indicating the existence of amorphous phases. This uneven agreement in the data and the large variation in experimental results indicate that the reaction mechanisms of CBGs in high-temperature oil wells remain tenuous in the literature. Consequently, this review offers important details regarding the reaction mechanisms of CBG applications in high-temperature oil wells.

The information presented in this study can also be useful in the fields of clay science, material science, chemical engineering, environmental engineering, construction, and building engineering. Different types of CBGs were discussed in this review, and CBG synthesis methods were summarized. Subsequently, the reaction mechanisms at high-temperature oil wells were studied. The factors affecting reaction mechanisms were analyzed, and the use of CBGs in oil wells was examined. The difficulties encountered while using CBGs in oil wells have opened new research avenues and are addressed in proposed solutions.

The rest of the study is organized as follows. The second section addresses other forms of CBGs, including kaolinite, illite, montmorillonite, and halloysite. The third section focuses on CBG synthesis techniques, and the fourth section discusses reaction mechanisms, including chemical reactivity, dissolution, gelation, polymerization, and growth. The fifth section presents the factors that affect reaction mechanisms, such as water content, Si and Al ratios, curing conditions, particle size and surface area, pH level, and alkaline activator concentrations. The sixth section addresses the use of CBG treatments in oil wells, and the final section discusses the challenges, prospects, and future trends of CBG application in oil well cementing operations.

2. Types of clay-based geopolymers

CBGs are an innovative class of materials that use various types of clay, such as kaolinite, illite, montmorillonite, and halloysite, as precursors to create sustainable and high-performance alternatives to traditional cement (Goracci et al., 2024). The following discussion presents the primary types of clay used in geopolymer cement production, along with their characteristics and applications. CBGs use clay as the main source of Si and Al for the geopolymerization reaction (Abdullah et al., 2018). This practice offers several advantages, including the reduction of energy requirements for manufacturing and increased sustainability (Dai et al., 2022). One type of CBG is (1) Kaolinite-based geopolymer (KBG), which is known for its high compressive strength, thermal stability, and low permeability, making it ideal for deep wells, high-temperature environments, and corrosive conditions. However, its reliance on calcination for activation increases energy consumption. Another type of CBG is (2) illite-based geopolymer (IBG), a moderately reactive clay that does not require high-temperature calcination, making it more energy efficient. It offers decent mechanical strength and thermal stability, making it viable for use in intermediate-depth wells. However, its lower reactivity compared to kaolinite limits early strength development, and achieving uniform performance may require a carefully designed mix and activation. (3) Montmorillonite-based geopolymer (MCG) is another type, which is a highly swelling clay with excellent sealing capabilities due to its expansive nature and high surface area. This makes it especially suitable for zonal isolation, lost circulation zones, and shallow to medium-depth wells. The downsides are its poor mechanical strength and high water demand, which can negatively affect long-term integrity and durability unless supplemented with strength-enhancing additives. The last type is (4) halloysite-based geopolymer, derived from a tubular clay mineral that is structurally similar to kaolinite but is often more reactive in its natural state. This geopolymer exhibits good strength and workability, with promising potential in CO_2-rich or geothermal environments. Nevertheless, halloysite availability is limited geographically, and its performance can vary depending on the degree of structural ordering.

2.1. KBGs

Kaolinite is a common clay mineral with the chemical composition $Al_2Si_2O_5(OH)_4$ (Equation (1)). Upon thermal treatment at temperatures of 500°C-800 °C, kaolinite transforms into metakaolin ($Al_2Si_2O_7$), a highly reactive amorphous phase suitable for geopolymerization. The properties of KBG have been extensively studied (Heah, 2011; Hounsi et al., 2014; Yunsheng et al., 2010). Metakaolin's amorphous structure enhances its reactivity with alkaline activators, leading to rapid geopolymerization (Tironi et al., 2012). Almenares et al. (2017) found that geopolymers derived from metakaolin exhibit high compressive strengths, often exceeding 40 MPa. Mañosa et al. (2024) noted that these geopolymers typically experience minimal drying shrinkage, contributing to dimensional stability. Alujas et al. (2015) also reported that they demonstrate good resistance to various chemical environments, including acids and sulfates. Due to their favorable properties, KBGs are very useful as (1) construction materials, such as precast elements and structural components; (2) protective

coatings requiring chemical resistance; and (3) oil well cementing applications, especially when tailored to high-pressure, high-temperature (HPHT) conditions (Balczár, 2016; Goracci et al., 2024; Kaya, 2022; Wang et al., 2023).

$$Al_2Si_2O_7 + 2NaOH + 9H_2O \rightarrow Na_2O.Al_2O_3.4SiO_2.11H_2O. \quad (1)$$

2.2. IBGs

Illite is a non-expanding, mica-like clay mineral commonly found in sedimentary rocks. It has a layered structure with potassium ions between the layers, which helps maintain the mineral's stability and non-expanding nature (Fernandez et al., 2011; Hu et al., 2017). Illite's structure consists of a 2:1 arrangement in which two silica tetrahedral sheets sandwich an alumina octahedral sheet. This configuration is similar to that of micas. Unlike some clay minerals, illite does not swell upon hydration. The presence of potassium ions between layers creates a strong bond, preventing water molecules from entering and causing expansion. This characteristic makes illite a non-expanding clay mineral. IBGs are moderately reactive (Equation (2)). Hu et al. (2017) explained that illite's reactivity is lower than that of metakaolin but can be enhanced through mechanical or thermal activation. In terms of thermal resistance, IBGs can withstand temperatures ranging from 300 °C to 600 °C and have good chemical stability. Chen et al. (2024a) found that IBGs exhibit good resistance to chemical attacks, including acids and sulfates. Because of these, some IBG applications are (1) fire-resistant materials and coatings; (2) cementing of deep oil wells, in which higher temperatures are encountered; and (3) stabilization of expansive soils in geotechnical applications.

$$Illite + NaOH \rightarrow Na_2O.Al_2O_3.SiO_2.H_2O + KOH. \quad (2)$$

2.3. MBGs

Montmorillonite is a smectite clay mineral characterized by its layered structure and high cation exchange capacity (Yang, 2018). Montmorillonite $(Na, Ca)_{0.33}(Al, Mg)_2Si_4O_{10}(OH)_2.nH_2O$ is a 2:1 clay mineral with high SiO_2 content. The alkaline activation process involves the dissolution of Si and Al units, followed by polycondensation, as seen in Equation (3). However, the exact stoichiometry varies, depending on the specific composition of the montmorillonite and the activator used (Hattaf et al., 2021; Muñiz-Villarreal, 2011; Simão, 2021). Montmorillonite, the primary component of bentonite clay, imparts swelling behavior to MBGs. Monticelli (2016) reported that montmorillonite can absorb significant amounts of water, leading to swelling, due to its unique layered structure and chemical composition. This swelling is primarily attributed to the mechanisms of crystalline swelling and osmotic swelling. Crystalline swelling is the initial stage in which water molecules enter the interlayer spaces of montmorillonite, leading to stepwise expansion, while osmotic swelling occurs upon further hydration with monovalent cations, such as Na^+. In addition, MBGs have good thermal stability. Diaz Caselles et al. (2023) reported that geopolymers derived from montmorillonite exhibit good thermal resistance, often withstanding temperatures above 400 °C. Salehi et al. (2016) found that MBGs possess high resistance to acidic environments, making them suitable for specific industrial applications. Due to these unique properties, MBGs can be used for (1) stabilizing contaminated soils and immobilizing waste; (2) cementing oil wells, particularly in CO_2-rich and acidic conditions; and (3) performing refractory applications.

$$Montmorillonite + NaOH \rightarrow Na_2O.Al_2O_3.SiO_2.H_2O. \quad (3)$$

2.4. Halloysite-based geopolymers (HBGs)

Halloysite is a naturally occurring Al_2SiO_5 clay mineral with a chemical composition similar to that of kaolinite ($Al_2Si_2O_5(OH)_4$). However, it is distinguished by its unique nanotubular morphology, which is more reactive in its natural state. Halloysite exhibits good strength and workability, with promising potential in CO_2-rich or geothermal environments. The presence of water molecules between its layers leads to the natural rolling of the sheets into tubular forms. This results in two common hydration states: (1) hydrated form (halloysite-10 Å), with a 10-Å interlayer spacing due to the presence of water molecules; and (2) dehydrated form (halloysite-7Å), with a reduced interlayer spacing of 7 Å after losing interlayer water. HBGs have nanotubular structures. This unique morphology of halloysite can enhance the mechanical properties of geopolymers. Adding halloysite can also improve the durability and toughness of the geopolymer matrix. Hattaf et al. (2021) found that geopolymers incorporating halloysite nanotubes can achieve compressive strengths of 45–50 MPa. In addition, HBGs can be used as (1) advanced composite materials due to their enhanced mechanical properties and as (2) self-healing concrete systems leveraging the nanotubular structure for encapsulating healing agents. HBGs also have (3) specialized applications in oil well cementing, in which enhanced toughness is required. Equation (4) shows the activation of halloysite.

$$Halloysite + NaOH \rightarrow Na_2O.Al_2O_3.SiO_2.H_2O. \quad (4)$$

Table 1 illustrates a comparison of CBG cements, which shows the geopolymer type, main composition, strength that each cement can withstand, thermal resistance, and key applications.

3. Synthesis methods

There are two methods used to produce CBG cement: (1) wet and (2) dry methods.

3.1. Wet method

The wet method involves the mixing of alkaline activators, such as NaOH and Na_2SiO_3, in liquid form with the precursor (clay) (Fig. 1a). This method is convenient due to its easy mixing process and its ability to produce a more homogenous mix of the alkaline activator and clay. In addition, the wet method allows for precise control of the alkaline activator solution, which is important for realizing the desired geopolymerization reaction. For instance, Rahman et al. (2016) designed CBGs using the wet mixing method to control the concentration of four alkaline activators. They reported that clay-based geopolymers generally show an increase in strength up to 14 days.

3.2. Dry method

In this method, the alkaline activator is milled in powder form together with the clay. The resulting dry mix is then activated with water, creating a one-mix geopolymer cement (Fig. 1b). This method offers advantages, such as increased commercial applications and easier handling of the alkaline activator. This method also does not require specialized equipment for mixing. Abbas et al. (2020)

Table 1
Shows the comparison of clay-based geopolymer cement.

Geopolymer Cement	Main Composition	Strength (MPa)	Thermal Resistance (°C)	Key Application
KBG	Kaolinite ($Al_2Si_2O_7$)	40–60	200–300	High-performance construction, coatings, and oil wells
MCG	Montmorillonite, Smectite	20–35	400+	Acid-resistant cement, waste stabilization, and CO_2 wells
IBG	illite, Shale clays	30–40	300–600	Refractory materials, fireproof coatings, and deep oil wells
HBG	Halloysite nanotubes	45–50	250–400	Nano-geopolymers, self-healing cement, composite materials

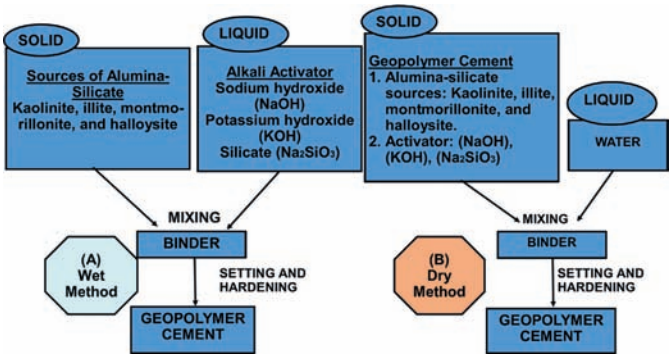


Fig. 1. Geopolymer cement production (a) wet method (b) dry method (Bayuaji et al., 2017).

produced CBGs from Egyptian kaolin clay using the dry method. They concluded that geopolymer concrete with a 30% metakaolin binder content has high mechanical strength (~56 MPa) and excellent corrosion inhibition in 3.5% NaCl solution (~80%) compared with cement concrete. Previous studies on different types of CBGs and their synthesis methods are presented in Table 2.

4. Reaction mechanisms

The reaction mechanisms involve the dissolution of Al_2SiO_5 source materials (e.g., clay) in an alkaline solution, followed by polycondensation to form a polymeric framework of Al–*O*–Si–O that acts as a binder (Zhu et al., 2022). The dissolution of these clay minerals, such as kaolinite, is enhanced at higher curing temperatures (above 65 °C). This is because at lower temperatures, the movement of water molecules in the alkaline activator is not intense enough to sufficiently cleave the interlayer spacing of the clay mineral crystals. However, the reaction usually starts with the dissolution of the Al_2SiO_5 source material at a high pH, thereby forming a supersaturated Al_2SiO_5 solution. In concentrated solutions, gel formation by condensation of oligomers releases water. The reaction categorization is given below. Fig. 2 shows the reaction mechanisms and the geopolymerization that takes place on geopolymer cement.

$$Si-Al\,Al_2SiO_5 + MoH_{(aq)} + Na_2SiO_3, \tag{5}$$

$$\downarrow$$

$$Si-Al\,Al_2SiO_5 + \left[M_z(AlO_2)\underset{x}{\leftarrow}(SiO_2)\underset{y}{\leftarrow}.nMOH.mH_2O\right], \tag{6}$$

$$\downarrow$$

$$Si-Al\,Al_2SiO_5 + \left[M_a\left((AlO_2)\underset{a}{\leftarrow}(SiO_2)\underset{b}{\leftarrow}\right).nMOH.mH_2O\right] \tag{7}$$

gelattion.

The reaction in these equations determines the amount of Si–Al material used. Equations (5) and (6) depend on Al–Si dissolution, particle size, and alkaline solution concentration. The volume of gel produced in the reaction in Equation (6) is dependent on the dissolution of Al or Si, whereas Equation (7) forms the amorphous geopolymer. However, the processing parameters determine how long it takes to make a geopolymer gel (Sinha et al., 2014).

4.1. Chemical reactivity

Chemical reactivity refers to the ability of Al_2SiO_5 minerals to undergo transformation into 3D polymeric networks during geopolymerization. The chemical reaction depends on the nature of both Al_2SiO_5 sources and the alkaline reaction used. Additionally, the chemical reactivity of clay begins at the surface and moves toward the edge of the structure, layer by layer, creating a bond within the structure to form an Al-substituted Si layer after the reaction with alkaline (Equation (8)). The Al-substituted tetrahedral units in the geopolymer structure contribute to the chemical reaction leading to the geopolymerization of the material (Jeong, 2020). Furthermore, since the Al–*O*–Al network in the molecular structure of 2:1 clay-like montmorillonite and illite is more stable than that of 1:1 clay-like kaolinite, their reactivity is lower. Several studies have indicated that pretreatments, such as thermal curing and high alkalinity, are required to accelerate the initial reaction of highly polymerized precursors, such as clay (Chen et al., 2024a; Frasson and Rocha, 2023). For example, Chen et al. (2024b) reported that at a lower calcination temperature (550 °C), only the interlayer water and physically adsorbed water are removed from most minerals, without physical changes in the crystal structure. This results in clay with low reactivity and little amorphous content during geopolymerization. By contrast, when the calcination temperature increases to 660°C-770 °C, the hydrogen atoms and the hydroxyl group from Al–*O*–H bonds in 1:1-type clay, such as kaolinite and halloysite, are separated. This process leads to the formation of amorphous Si and Al phases, thus enhancing clay reactivity. Alternatively, at higher calcination temperatures (850 °C), the crystal structures of 2:1-type clay minerals, such as illite and montmorillonite, are destroyed, resulting in the formation of a more amorphous phase. This is because the distribution of octahedral vacancies in 2:1 layered minerals has a strong effect on the dihydroxylation temperature, thereby requiring a higher calcination temperature to disrupt the crystal structure.

$$Mn[-(Si-0_2)z-Al-0]n.\,wH_20. \tag{8}$$

4.2. Dissolution

Dissolution occurs when a solute, such as a solid material, is distributed into a solvent (e.g., a liquid) to form a homogeneous solution. During the dissolution reaction, the individual particles of the solute are separated from one another and surrounded by solvent molecules, resulting in the formation of a solvated solute species that is dispersed throughout the solvent (Chen et al., 2010; Panagiotopoulou, 2007; Dassekpo, 2022). This reaction releases soluble Al and Si ions, which are essential for subsequent polymerization reactions (Equation (9)). Dissolution occurs in

Table 2
Previous studies on different types of CBG and their synthesis method.

Reference	Types of Clay	Synthesis Method	Reaction Mechanism	Findings	Limitation
Rovnaník (2010)	Montmorillonite	Calcination at 750 °C followed by alkaline activation	Montmorillonite formation, enhanced reactivity, and geopolymer network formation.	• Enhanced mechanical properties with calcination. Compressive strength of 50 MPa achieved. Improved durability and reduced porosity. • Good compressive strength (40 MPa). Improved workability and setting time with KOH compared to NaOH. Enhanced chemical resistance.	Requires high curing temperatures; alkali type influences setting
Yunsheng et al. (2010)	Halloysite	Calcination and blending	Calcination and blending	• Increased early and long-term strength, reduced porosity, and improved resistance to acid attack. • Superior mechanical strength and stability under harsh conditions.	Complex handling of red mud; bentonite reduces reactivity
Davidovits (2013)	Montmorillonite	Calcination at 750–800 °C	Polcineycondensation of dissolved silicate and aluminate species	• Enhancement in strength, reduced environmental impact • Pioneering study showing MBGs have excellent mechanicalproperties and the potential for wide-ranging applications.	Energy-intensive process; limited raw material availability
Assaedi et al. (2016)	Kaolinite	Two-step synthesis: calcination at 800 °C, followed by geopolymerization	De-hydroxylation of kaolin to metakaolin, followed by geopolymer formation	• High compressive strength (55 MPa). Improved thermal stability and acid resistance. Two-step process enhances mechanical properties. • It will make the setting time to be fast also improve the mechanical properties, in addition making the compressive strength to be 48 MPa. Energy-efficient process with reduced curing time.	Two-step synthesis increases processing complexity
Xie and Kayali (2014)	Metakaolin	Calcination and raw use	Pozzolanic and geopolymeric reactions	• Significant improvement in mechanical properties and durability; enhanced acid resistance.	Metakaolin can reduce reactivity; variable results.
Tironi et al. (2014)	Kaolinite Clay	Alkali-activation with sodium hydroxide and curing at elevated temperature	Geopolymerization enhanced by heat, leading to dense microstructure	• Very high compressive strength (60 MPa). Enhanced microstructural properties and reduced water absorption. Optimal curing temperature at 70 °C for 24 h.	Requires elevated curing temperature (70 °C); energy demand.
Hu (2019)	Montmorillonite	Alkaline activation with various activators	Dissolution and polycondensation	• The type of alkaline activator significantly influences the properties of the resulting geopolymer. Sodium silicate yields the best results.	High alkali usage may increase cost and safety concerns.
Ridha (2020)	illite	Calcination of volcanic clay	Pozzolanic reaction	• Cracking and sulfate attack; enhanced durability.	Susceptible to cracking and sulfate attack under certain conditions.
Figueiredo (2021)	illite	Alkaline activation	Geopolymeric reaction	• Significant improvement in compressive strength and durability; reduced chloride permeability. • Superior mechanical strength and stability under harsh conditions.	Handling and disposal of illite can pose environmental risks
Burduhos et al. (2022)	Kaolinite	Calcination at 750–800 °C	Pozzolanic reaction	• Increased strength and durability; reduced chloride permeability and sulfate attack. • Improved mechanical properties, durability, acid resistance	Energy-intensive calcination; cost of metakaolin can be high
Zhu et al. (2022)	Halloysite	Raw use with alkaline activation	Cation exchange and pozzolanic reaction	• Improved resistance to sulfate and acid attacks; enhanced mechanical properties. • Halloysite-based geopolymers show lower mechanical strength compared to metakaolin but still possess significant binding properties.	Lower strength than halloysite; requires optimization of activators

Chen et al. (2023)	Halloysite	Calcination and raw use	Pozzolanic and filler effect	• Improved mechanical properties, significant reduction in porosity and permeability.	Halloysite has lower reactivity than metakaolin; mixed results in consistency
Jiang et al. (2024)	illite	Calcination and raw use	Pozzolanic and geopolymeric reactions.	• Enhanced mechanical strength and durability, improved resistance to chemical and physical attacks. • Different types of clay also affect the properties of the geopolymers, with kaolinite providing the best results in terms of strength.	illite shows lower reactivity; variation in clay types affects consistency
Kryvenko et al. (2024)	Kaolinite	Calcination at high temperatures	Pozzolanic reaction	• Enhanced durability against sulfate attack and freeze-thaw cycles; improved compressive strength. • Improved resistance to thermal reaction	High calcination temperatures increase energy demand
Pelosi et al. (2024)	Various Clays	Alkaline activation with optimized curing (60–80 °C)	Geopolymerization via dissolution of aluminosilicates, forming N-A-S-H gels	• Enhanced mechanical properties, reduced carbon emissions, improved durability, and resistance to extreme conditions	Excessive curing temperatures can degrade long-term structural integrity
Salim and Moro (2025)	Calcined Halloysite	Replacement of GGBFS and fly ash with 2.0 wt% Hal750 °C	Formation of additional geopolymer gel phases (C-A-S-H and N-A-S-H)	• 28-day compressive strength of 72.9 MPa; nanotubular morphology acts as reinforcing fibers	Excessive Hal750 °C (>4.0 wt%) reduces strength due to low geopolymerization and porous microstructure

three stages: (1) disintegration of solute particles, in which the solid solute particles are separated from one another either through mechanical agitation or the action of solvent molecules; (2) solvent–solute interactions, in which solvent molecules surround the individual solute particles, forming solvation shells via forces known as hydrogen bonds, electrostatic interactions, and van der Waals forces; and (3) dispersion in the solvent, in which the solvation solute particles become dispersed throughout the solvent, resulting in the formation of a homogeneous solution (Khater, 2013). However, reactions, such as dissolution, hydrolysis, and condensation, occur during the creation of geopolymers, contingent on the Si concentration inside the system. Condensation reactions can happen among Si species or between Si and Al ions. The concentrations of Al or Si in the solution gradually rise because of the different products from Al_2SiO_5 dissolving in it. After Al and Si concentrations equalize, the existing solid or gel phases stabilize (Assi et al., 2018). The equilibrium-producing bidirectional processes in the Al_2SiO_5 molecule determine its behavior. The breakdown of the Al–*O*–Si surface is facilitated by the solvent, resulting in the generation of soluble species connected to the forward processes. This is again contingent on the pH level.

$$Al_2Si_2O_5(OH)_4 + 4NaOH + 4H_2O \rightarrow 2Na_2SiO_3 + 2NaAlO_2 + 6H_2O. \quad (9)$$

4.3. Gelation

Gelation is a process in which a liquid precursor solution transforms into a solid material. During gelation, the alkali activator solution reacts with Al and Si materials to form a gel-like structure; this process can be achieved through the physical or chemical cross-linking of the precursor molecules (Winter, 2016). Physical cross-linking occurs when noncovalent connections are formed between molecules, such as hydrogen bonds or pi stacking (π-π stacking), which can lead to the assembly of supramolecular structures, such as β-sheets (Gulrez et al., 2022). Winter (2016) reported that chemical cross-linking is the process by which molecules create covalent bonds with one another, typically through chain-growth polymerizations initiated by stimuli, such as redox initiation or photo initiation, pH and temperature of the solution, and the presence of additives or catalysts, as shown in Fig. 3. For instance, the use of divalent cations, such as calcium ions, can induce the gelation of anionic polymers, such as alginate. However, the mechanical properties of gels, such as their shear modulus and elastic modulus, are important for understanding their behavior in different environments and applications (Gulrez et al., 2022). Therefore, the gelation reaction mechanism can be classified into two major categories: (1) chemical gelation, which is known as covalently cross-linked networks; and (2) physical gelation, which is held together by molecular entanglements and secondary forces (Toniolo, 2018). A recent analysis by Lv et al. (2024) found that environmental factors, such as pH, humidity, and temperature, can also influence the gelation process. A higher pH can accelerate the gelation reaction, while a lower pH can slow it down. The presence of an interconnected structure also affects the gelation process. Drabczyk et al. (2023) observed that the formation of a rigid, interconnected gel structure through chemical gel is responsible for the early-age, long-term, and high compressive strength of CBGs. Moreover, the degree of chemical gelation controls the porosity, pore size distribution, and overall density of the CBG. A well-developed gel structure leads to a denser microstructure. In addition, a well-connected gel structure formed through chemical gelation enhances the durability of CBG cement against various environmental attacks, such as acid, sulfate, and high-temperature exposure (Drabczyk et al., 2023).

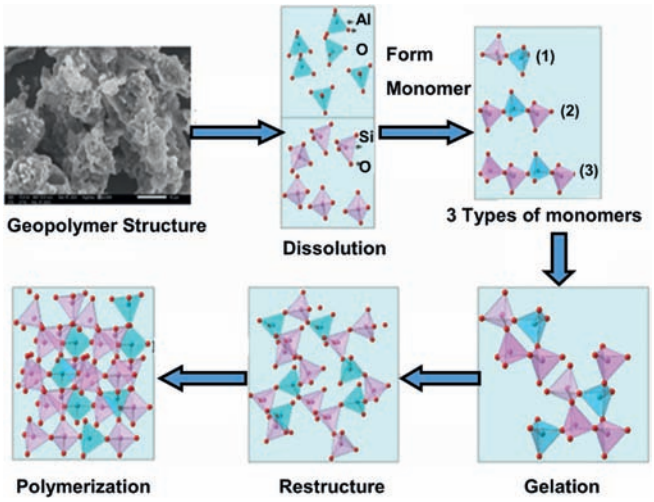


Fig. 2. Schematic diagram of microstructural changes on geopolymer cement (Adjei et al., 2022).

Equations (10) and (11) show the reaction mechanisms.

$$SiO_2 + NaoH \rightarrow Na_2SiO_3 + H_2O, \quad (10)$$

$$Al_2O_3 + NaoH \rightarrow NaAlO_2 + H_2O. \quad (11)$$

4.3.1. Physical gelation

Physical gelation in CBG systems refers to the early-stage transition from a fluid-like mixture to a semi-solid, gel-like structure due to physical interactions rather than full chemical geopolymerization. This process plays a crucial role in the initial setting behavior, workability, and structural development of the geopolymer before hardening occurs (Tang et al., 2024). When clays are mixed with an alkaline activator (NaOH or KOH), the clay particles begin to swell and disperse. Surface charges on clay particles, especially in montmorillonite, lead to electrostatic repulsion and attractive van der Waals forces, causing the formation of a 3D particle network (López-Santiago et al., 2024). This network traps water and increases viscosity, leading to physical gelation, which is a reversible, nonpermanent phase. Hydrogen bonding and interlayer cation exchange in some clays also promote the formation of a physically entangled structure. However, physical gelation occurs before the full geopolymerization reaction, stabilizing the mix and preventing segregation or excessive bleeding. It enables early cohesion of the material, which is particularly important in oil well cementing, where maintaining pumpability and providing initial support are critical. Fig. 4 shows the reactions that occur during the physical gelation of CBG cement (Tang et al., 2024).

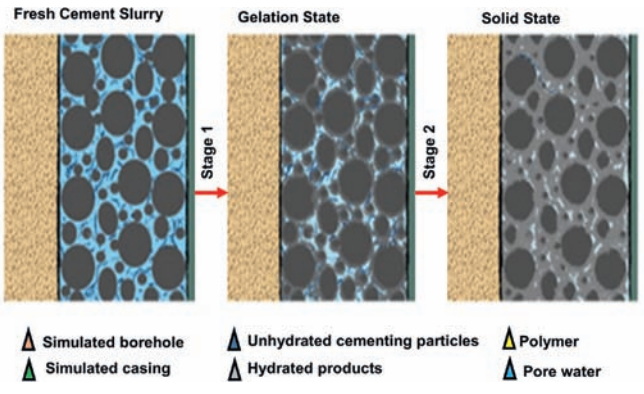


Fig. 3. Gel formation process on clay-based geopolymer.

4.3.2. Chemical gelation

Chemical gelation refers to the irreversible transformation of a liquid-phase system into semisolid or solid gel through chemical bonding during geopolymerization. Unlike physical gelation, which is governed by weak physical interactions, chemical gelation involves the formation of permanent covalent bonds between dissolved Si and Al ions, leading to a robust interconnected Al_2SiO_5 network (Fig. 5). The chemical gelation process in CBGs enhances the material's mechanical properties through a sequence of intricate events that result in the development of a solid structural gel. This process typically involves the dissolution of Al_2SiO_5 material, such as clay, in an alkaline solution, followed by the formation of the gel through chemical condensation (Giacobello et al., 2022). It is typically used to form strong gels that are resistant to temperature changes or other external conditions.

4.4. Polymerization

The polymerization reaction of CBGs involves the transformation of amorphous Al_2SiO_5 into a 3D polymeric network through a chemical reaction with alkaline activators. The primary components of this reaction are Si and Al, which are derived from clay minerals (Wang et al., 2019b). When clay is mixed with an alkaline solution, these components are dissolved, and subsequently, Si–*O*–Al–O frameworks are formed. The polymerization process begins with the dissolution of SiO_2 and Al_2O_3 particles in the activator's alkaline media, after which these particles change into a spatial chain of Al and Si polymer structures (Abdullah et al., 2021; Fiorentini et al., 2023). The composition of Al_2SiO_5 determines the type of geopolymer formed. Thus, the polymerization process in geopolymer cement takes place during the activation of Al_2SiO_5 (Chindaprasirt and Chalee, 2014; Kupwade-Patil and Allouche, 2013; Medri et al., 2020). Al_2SiO_5 is exposed to an activator's alkaline medium, which causes the resulting Al_2SiO_5 oxides to dissolve in the mortar's high pH. This process creates a gel, which is known as the oligomers established on Si–*O*–Al and Si–*O*–Si polymer links. This gel creates a polymer structure when it hardens, retaining aggregates and unreacted particles within the content. Several monomer molecules join to form a polymer during this process. This polymerization can be classified as (1) in situ polymerization or (2) polymer-modified cement (PMC).

4.4.1. In-situ polymerization

This is a polymerization process that occurs within the cement matrix itself, rather than as a separate step. This technique involves the incorporation of monomers into the cement mixture, which then polymerize in situ, forming a polymer network that enhances the properties of the cement structure (Fiorentini et al., 2023; Li and Li, 2018; Sufian Badar et al., 2014). Additionally, as seen in Fig. 6, this technique can increase the cement's strength, durability, and mechanical qualities. In situ polymerization can significantly increase the flexural strength of the cement-based composites, thereby making them more durable and resistant to cracking under HPHT conditions. It also improves sustainability, increasing its resistance to freeze-thaw cycles, carbonation, and sulfate attack (Lloyd et al., 2010). This process can improve the workability of the cement mixture because it will make it easier to mix and place; by controlling the types and amounts of monomers used, the properties of PMC are tailored to its specific applications (Fiorentini et al., 2023).

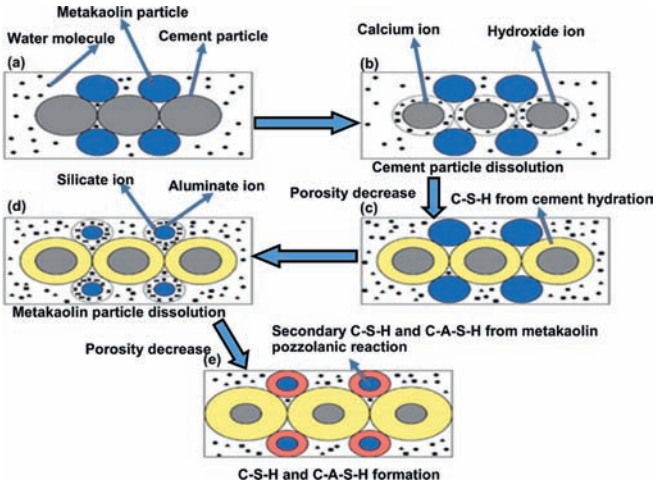


Fig. 4. Schematic illustration of physical gelation of cement (Tang et al., 2024).

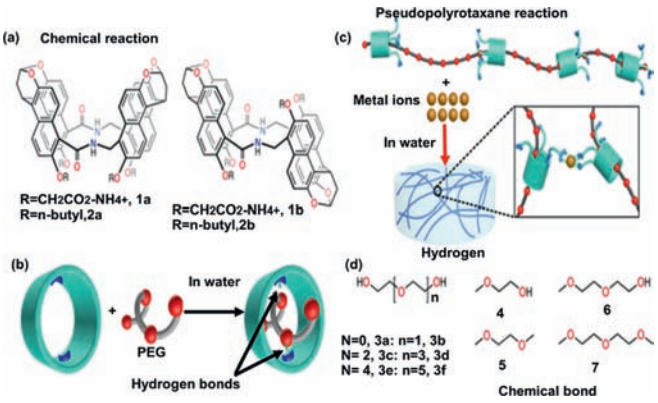


Fig. 5. Chemical reaction on gelation (a) chemical reaction (b) hydrogen bonds (c) pseudopolyrotaxane reaction (d) chemical bonds (Lv et al., 2024).

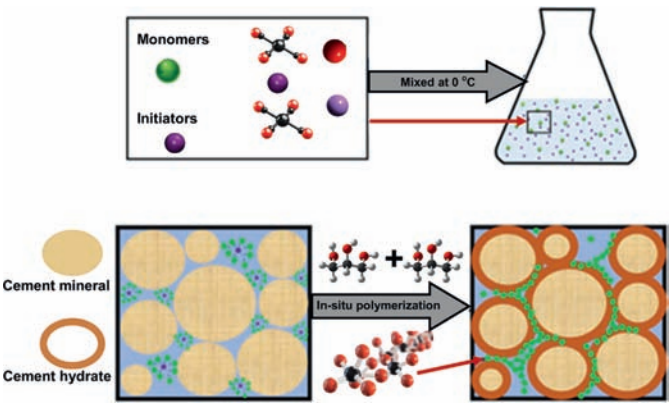


Fig. 6. In-situ polymerization process (Sun et al., 2023).

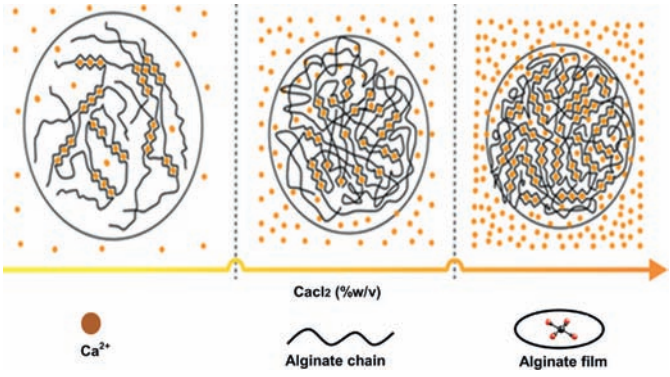


Fig. 7. Demonstrate the growth gelation process on CBG cement (Song et al., 2023).

4.4.2. PMC

PMC is a composite material that incorporates polymeric material into the geopolymer mixture. This modification enhances the properties of the geopolymer, thereby making it more durable and easier to use (Hounsi et al., 2014; Meng et al., 2024; Pasupathy et al., 2021). The polymers used in PMC may be added in different forms, such as re-dispersible dry polymers, latex, or water-soluble polymers. These polymer forms can be added to the geopolymer mixture or applied as a coating after the cement has hardened; the addition of polymers makes the geopolymer more workable, durable, and effective, thereby reducing the amount of water needed and improving the overall application (Li et al., 2022). Song et al. (2023) reported that the use of polyacrylamide polymers is required to improve the strength and durability of CBG cement, enhancing its viability in application. The polymer can reduce the water-to-cement ratio, thereby increasing its compressive strength, flexural strength, and tensile strength. The polymer also assists in preventing the separation of materials and further enhancing their strength. The decrease in water permeability protects the geopolymer from damage caused by repeated freezing and thawing. Zhu (2014) found that the polymer forms a film that fills capillary holes and microcracks in the cement matrix, which then improves resistance to water penetration by obstructing water flow routes. In addition to offering improved chemical resistance, PMC offers greater protection against typical chemical attacks, such as chloride ion penetration, which can corrode reinforced cement.

4.5. Growth

Growth is the process by which a material undergoes structural CBG rearrangement. This phase is vital in shaping the microstructural and pore distribution on CBGs. It influences three important physical properties: (1) strength, (2) permeability, and (3) durability. During the growth stage, nuclei that have formed in the earlier stages of geopolymerization reach a critical size, allowing crystals to begin to develop. These crystals contribute to the overall solid framework of the material. The growth phase is vital for establishing the material's performance characteristics and stability (Agi et al., 2021; Duxson et al., 2007). In the growth phase of CBG formation, several intricate processes are crucial for defining the final material's structure and properties. This phase comes after the nucleation stage, in which small precursor particles (or nuclei) form within the system. Moreover, Agi et al. (2022) explained that after nucleation, nuclei must grow to a critical size to begin the crystallization process. This involves the incorporation of additional reactive species into the nuclei, increasing their size. The critical size is important because only nuclei that surpass this size threshold can evolve into stable crystals, while smaller nuclei may dissolve back into the solution. In addition, as the nuclei reach the critical size, crystallization occurs. Pawłowski et al. (2022) reported that the growth phase does not end immediately after initial crystallization. The structure can continue to evolve, particularly if the geopolymer is exposed to moisture or elevated temperatures. Over months or even years, continued

crystallization, densification, or changes in pore distribution occur. This aging process can improve the material's strength and influence its durability under certain environmental conditions. Two structures are typically formed based on the synthesis method: (1) polyhedral and (2) zeolite-like structures. However, polyhedral structures form because of cross-linking between Si and Al tetrahedra, which can further aggregate to form clusters. Zeolite-like structures may also develop in some geopolymers. Fig. 7 shows the growth that takes place in CBG cement.

5. Factors affecting reaction mechanisms

The reaction mechanisms of CBGs are influenced by several factors: (1) water content, (2) Si and Al ratio, (3) curing conditions, (4) particle size and surface area, (5) pH level, (6) alkaline activator concentration, and (7) presence of impurities. Merline et al. (2013) reported that the type, concentration, and modulus of the SiO_2–Na_2O ratio and the alkali activator (NaOH) affect the dissolution of Al_2SiO_5. They also influence pH and polymerization kinetics; high temperature and durability affect the curing time.

5.1. Water content

Water content is the proportion of water present in a substance, usually expressed as a percentage of the overall weight or volume of the substance. Water content influences how geopolymers form, are structured, and exhibit flow behavior. Furthermore, water serves as a medium for oligomer hydrolysis, polycondensation, ions that have dissolved, or dissolution. Water also gives the geopolymer mix good flowability; adequate water to react with the mixtures facilitates mixing and serves as a vehicle for ion exchange (Wong and Buenfeld, 2009; Gu, 2022; Škvára, 2009). However, excessive water during geopolymer synthesis is a persistent concern. An overabundance of water moves ions out of the reaction zone and dilutes the system's alkalinity (Castillo et al., 2021). Nevertheless, water is essential to geopolymerization, particularly for hydrolysis, to dissolve Al^{3+} and Si^{4+} ions, as well as to the disintegration of solid particles. A higher water content in the late stage of this process accelerates the polycondensation rate (Barría et al., 2023). This may be attributed to the continued dissolution of leftover solid particles and hydrolysis-produced Si^{4+} and Al^{3+} ions, as water is needed for polycondensation processes with synchronous dissolution, even during the final stages of geopolymerization. According to a laboratory investigation by Rajamane (2011), the reaction rate can be considerably reduced by using either a low water content of 5 mol or a high water content of 5000 mol. In their laboratory experiment, the OH concentration was reduced at a high water content. They also found that the mechanical properties of CBGs include compressive strength and flexural strength, which are adversely affected by a high water content. As the water content increases, compressive strength decreases because of the formation of more capillary pores within the wall of the material. For example, compressive strength values dropped from 54.3 MPa to 29.1 MPa with an increase in water content. This reduction is attributed to the dilution of the activator concentration necessary for effective geopolymerization, which leads to less favorable reactions and lower strength. Fig. 8 shows the effect of water content on CBG cement. Optimizing water content is essential for enhancing the performance of CBGs in oil well cementing, as it directly affects workability, strength development, setting time, and durability. In geopolymer systems, water serves primarily as a medium for dissolving and transporting alkali activators but does not become chemically bound in the final structure. Therefore, excess water leads to increased porosity and reduced strength, while insufficient water impairs pumpability and reaction efficiency (Wong and Buenfeld, 2009). The optimization process begins by selecting an appropriate liquid-to-solid ratio, typically ranging from 0.4 to 0.6 by weight, and adjusting it based on the specific clay type. For instance, swelling clays, such as montmorillonite, require more water due to their high absorption capacity, while kaolin or halloysite demand less. However, chemical additives, such as superplasticizers, can be used to reduce water content without sacrificing flowability. These improve the workability of the mix while maintaining low porosity and high strength.

5.2. Si and Al ratio

Optimizing the Si–Al ratio is a critical factor in enhancing the performance of CBGs for oil well cementing. The Si–Al ratio directly influences the geopolymer's structural framework, mechanical properties, chemical resistance, and setting behavior, all of which are essential under downhole conditions (Ahmari and Zhang, 2012; Al Ani et al., 2024). In geopolymer chemistry, Si and Al atoms form the backbone of the 3D Al_2SiO_5 network through polymerization reactions. The ideal Si–Al ratio typically ranges from 1.0 to 3.5, depending on the desired properties. Lower ratios (closer to 1) lead to a more rigid and dense structure, improving early strength and thermal resistance, which are ideal for high-temperature wells. However, excessively low Si–Al ratios can cause brittleness and reduced workability. By contrast, higher Si–Al ratios result in more flexible structures with better flowability but potentially lower compressive strength and longer setting times, which may not be suitable for high-pressure, high-load applications (Ahmari and Zhang, 2012; Sindhunata, 2006; Wang et al., 2021a). A low Si–Al ratio leads to the formation of undesirable microstructures, whereas an optimal ratio enhances compressive strength and durability by forming a denser, more uniform gel structure. To create a geopolymer gel with robust interparticle bonding and enhanced mechanical strength, Si is required. SiO_2 is hydrolyzed by Si ions and condensed among themselves to produce oligomeric Si when the ratio of Si–Al exceeds 1. At a Si:Al ratio of 1, condensation between the Al and Si ions creates poly[sialate] structures. As oligomeric silicates condense with Al [OH], poly[sialate-siloxo] and poly[sialate-disiloxo] polymer structures are formed, creating a 3D network (Mahmoud et al., 2024). However, a study by Davidovits (2008) showed that more Si–*O*–Si bonds form as the Si:Al ratio increases to 1.7, increasing the volume of the geopolymer gel. Increasing the SiO_2–Al_2O_3 ratio from 2.0 to 4.0 speeds up the initial pace of the reaction but also causes the paste to harden before the reaction is completed (Algaifi et al., 2021). Additionally, the gel formation of geopolymers is improved using highly reactive SiO_2, and the resonance position and shape of the geopolymers may be predicted using the specimen's Si:Al ratio (Davidovits et al., 2020; Medri et al., 2020). However, Davidovits (2013) argued that the geopolymer composition should be within the range indicated in Table 3 to achieve high strength and form long-lasting products. He concluded that the optimal ratios for Al_2O_3–Na_2O and Al_2O_3–SiO_2 are about 4.00 and 1.00, respectively. Table 2 (Davidovits, 2013) shows a slightly higher range of 3–3.6, which is the ideal SiO_2–Al_2O_3 ratio; increasing SiO_2–Al_2O_3 ratios improves mechanical characteristics. The setting behavior of geopolymers is influenced by their Al content, whereas their mechanical strength is more strongly associated with their Si content. This might be attributed to $Al_6Si_2O_{13}$ dissolving more readily in the direction of the geopolymerization reaction at an increased Si concentration (Chezan et al., 2023).

5.3. Curing conditions

Curing conditions have a significant effect on CBG characteristics and performance. High temperatures accelerate the dissolution of reactive species and chemical reactions, thereby increasing the walls between the Al_2SiO_5 source and the alkaline solution during the synthesis of geopolymers; this, in turn, promotes the formation of alkali-activated materials (Hassan et al., 2019; Pangdaeng, 2014; Wang et al., 2020a; Zuhua et al., 2009). Curing temperature and curing time also have major effects on mechanical strength and geopolymerization kinetics. The final product's structure depends significantly on the temperature of the reaction and the duration of the curing process (Duxson, 2007). Curing temperatures roughly around 60 °C and 80 °C are recommended for enhancing CBGs' mechanical properties, accelerating the dissolution of Al_2SiO_5 species, and promoting rapid geopolymer gel formation. They lead to faster setting and early strength gain, which are particularly beneficial for high-temperature or geothermal wells. However, excessively high temperatures may cause premature setting or microcracking due to thermal stresses, especially in low-viscosity or water-rich systems (Yılmaz et al., 2024). Optimizing curing conditions is vital for ensuring the performance and long-term durability of CBGs in oil well cementing applications. Curing affects geopolymerization, influencing strength development, setting time, chemical stability, and microstructural integrity factors, which are critical under the HPHT conditions of oil wells. Extended curing times allow for more complete geopolymerization, leading to the increased formation of cementitious products. For instance, increasing the curing time from 90 days to 365 days has been shown to enhance effective shear strength parameters, such as cohesion and friction angle, in treated clay (Wang, 2017). In laboratory investigations, the effects of curing conditions on CBGs have been thoroughly investigated. Tables 4 and 5 show the effects of curing time and temperature, respectively, on the reaction mechanisms of CBGs. Fig. 9 illustrates the curing time comparison between geopolymer cement and class G cement, showing that geopolymer cement outperforms class G cement (Sajedi and Razak, 2011). Curing time plays a significant role; while most CBGs achieve substantial strength within 24–72 h, the total curing duration should reflect operational requirements and placement schedules. Although longer curing may improve strength and chemical stability, it must be balanced against the need for timely well completion.

5.4. Particle size and surface area

For CBG cement to function properly, a connection between particle size and surface area is essential. Throughout geopolymerization, particle size affects how quickly chemical reactions occur. This is because there is more surface area available for reaction when the particles are smaller. By contrast, larger particles could cause the reaction to slow down (Antoni et al., 2015; Izquierdo et al., 2010; Cheng et al., 2024). A higher surface area means that more reactive sites are available for the chemical reactions necessary for geopolymer formation.

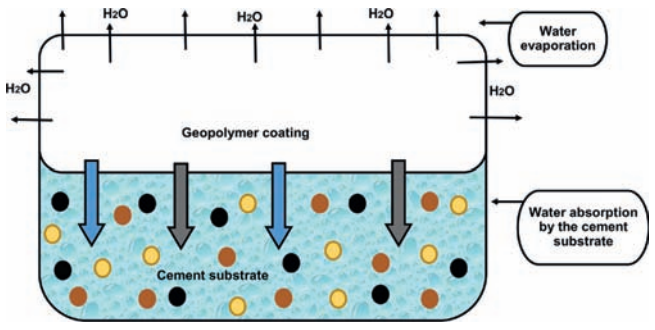


Fig. 8. It shows the effect of water acting on CBG cement.

5.4.1. Particle size

Particle size is important, as it affects the properties and performance of CBGs, particularly their mechanical strength, setting time, and overall reactivity (Antoni et al., 2015; Görhan et al., 2012; Li et al., 2021). Fine particles also accelerate dissolution by reacting with Al and Si species, leading to quicker polymerization. Smaller particle sizes generally increase the specific surface area, enhancing the reactivity of clay materials during geopolymerization (Kohout et al., 2023). The mechanical performance of CBG composites is notably affected by particle size. Furthermore, finer particle distributions have been shown to enhance Al leaching rates, which can affect the overall stability and durability of the geopolymer structure. A smaller particle size contributes to a shorter initial setting time for geopolymer binders. This rapid setting can be disadvantageous in oil well cementing applications in which long-time curing is necessary (Nwaichi et al., 2024; Wang et al., 2017). Slaný et al. (2023) reported that finer particles not only improve mechanical strength but also influence setting time. Smaller particles dissolve more quickly in the alkaline solution used in geopolymer formation, resulting in faster gel formation and hardening. This property may be ideal for applications requiring fast strength gain; however, it can be problematic when longer workability or extended curing times are necessary, such as in oil well cementing. In such applications, rapid setting may limit the time available for proper placement and bonding, potentially compromising performance. While smaller particle sizes enhance reactivity and strength, they can also introduce challenges in specific industrial applications. In oil well cementing, for example, long curing times are essential to allow proper hydration, bonding, and crack resistance. Rapid setting due to finer particles may hinder the ability to achieve the necessary long-term performance, highlighting a trade-off between reactivity and application-specific requirements (Abbas et al., 2024a, 2024b; Al Ani et al., 2024; Castillo et al., 2021; Tahmasebi et al., 2021). Table 6 presents a summary of the effects of particle size on CBG cement.

5.4.2. Surface area

The surface area of clay materials is a critical factor that extensively influences the properties and performance of CBGs (Demir et al., 2019; Han et al., 2023; Konan et al., 2009). Different clay types exhibit varying surface areas and reactivities, which are partly determined by their crystallinity. Highly crystalline clays generally have lower surface areas than amorphous or disordered clays. Structurally, CBGs exhibit a mesoporous structure, with widths of about 2.0–50 nm. Higher specific surface areas facilitate better interaction between the clay particles and the alkaline activators used in geopolymer synthesis (Chindaprasirt et al., 2022; Petrus et al., 2021). This leads to improved Al or Si species dissolution, which is essential for the formation of geopolymeric gel. Duxson (2005) reported that the higher the surface area of the raw materials, the more active the sites for chemical reactions during geopolymerization. This increases the reactivity of CBGs, enhances the rate of strength gain, and improves the overall performance of the geopolymer cement. As discussed earlier, the smaller particle sizes in CBGs lead to an increased surface area. For instance, finer particles can exhibit a significant increase in surface area, which enhances the material's reactivity and adsorption capacity (Abbas et al., 2024a; Maged et al., 2023).

5.5. pH level

The pH level influences the dissolution rate of Al and Si species from the raw materials, which is crucial for forming the geopolymer gel. A higher pH can enhance the reactivity of the precursors, leading to improved geopolymerization (Babaee and Castel, 2016; Ho, 2018; Pasiakos, 2020). However, when the pH is too low, the reaction may not proceed efficiently, resulting in a less cohesive material. Conversely, an excessively high pH level can lead to the excessive dissolution of Al_2SiO_5, potentially disrupting proper setting and reducing strength development (Wong, 2022). Castillo et al. (2021) noted that the pH level affects microstructure, including porosity and density. A proper pH balance leads to a more homogeneous and less porous structure, thereby enhancing the material's overall properties. Conversely, extremely high pH levels can reduce the workability of the mixture due to the rapid onset of geopolymerization. Adjusting the pH to the optimal range can help maintain good workability while ensuring proper setting (Abbas et al., 2024b; Zhang et al., 2010). Wang et al. (2019a) reported that the initial pH level of CBGs is vital in the geopolymerization reaction. For instance, an increase in the activator-to-binder ratio has been shown to elevate the pH significantly; for a 10% geopolymer content, the pH rose from 7.2 in untreated clay to 11.75. This alkaline environment is necessary for the optimal dissolution of Al_2SiO_5 phases. Geopolymerization typically requires a highly alkaline environment with an optimal pH range of 11–14. Within this range, the alkali activator, often combined with sodium silicate, facilitates the breakdown of the Si–O and Al–O bonds in the clay. The dissolution process releases silicate and aluminate species into the solutions, enabling them to reorganize into a solid Al_2SiO_5 network. A sufficiently high pH ensures rapid reaction kinetics, leading to quicker setting times and earlier strength development, which are crucial for oil well operations requiring fast pressure resistance. Additionally, the buffering capacity of geopolymer-treated clay against sulfate solutions is influenced by its pH level because different sulfate solutions will alter the pH at varying rates, thereby affecting the geo-mechanical properties of the treated clay over time (Al Ani et al., 2024; Kelestemur and Demirel, 2015; Abutu et al., 2025a, 2025b). Optimizing the pH level is a fundamental aspect of improving the performance of CBGs in oil well cementing. The pH governs the dissolution of Al_2SiO_5 materials, the rate of geopolymerization, and, ultimately, the mechanical strength and durability of hardened cement.

5.6. Alkaline activator concentration and Solid–Liquid ratio

A high activator concentration enhances the hydration reaction and the degree of geopolymerization by promoting Al_2SiO_5 dissolution and depolymerization (Knight et al., 2007; Panagiotopoulou, 2007). This results in strong alkaline metal cation binding in the structure and a reduction in other free ions, thereby compacting the geopolymer structure (Xu et al., 2021). A compacted geopolymer structure might develop cracks. Therefore, the number of cracks in the geopolymer increases with an increasing activator concentration and decreases with an increasing solid–liquid ratio. The higher the activator concentration, the higher the degree of polymerization, resulting in a high gel content (>50%) and severe shrinkage. For instance, when the activator concentration was small, no shrinkage cracks were found on the geopolymer surfaces, as seen in Fig. 10. However, the geopolymer exhibited more shrinkage cracks with increasing activator concentrations. Optimizing the alkaline activator concentration and solid-to-liquid ratio is key to enhancing the performance of clay-based geopolymers for oil well cementing. These two parameters significantly influence the reaction kinetics, mechanical strength, setting time, workability, and long-term durability of the geopolymer slurry under downhole conditions. Both alkaline activator concentration and solid-to-liquid ratio must be carefully optimized to ensure that the clay-based geopolymer performs reliably in oil well environments. For instance, Xu et al. (2021a) observed that the optimum activator concentration is 40%, and the solid–liquid ratio is 1.25:1.

Table 3
Recommended oxide molar ratios of geopolymer (Davidovits et al., 2013).

Molar ratios of oxides	Ranges
Al_2O_3/SiO_2	3.52–4.52
Al_2O_3/Na_2O	0.84–1.23
Na_2O/H_2O	15–17.54
SiO_2/Na_2O	0.21–0.29

5.7. Presence of impurities

The presence of impurities in CBGs can significantly influence the reaction mechanism, geopolymerization, and properties of the resulting material. These impurities often interact with the Al_2SiO_5 network and may introduce secondary reaction mechanisms that modify the microstructure, mechanical strength, durability, and chemical resistance of the geopolymer (Chitsaz and Tarighat, 2021; Marín et al., 2021). These impurities are calcium (Ca^{2+}), iron (Fe^{2+}/Fe^{3+}), magnesium (Mg^{2+}), sulfur (S^{2-}, SO_4^{2-}), carbonates (CO_3^{2-}), and chlorides (Cl^-), which can disrupt or alter geopolymerization. Ca^{2+} is a common impurity in Al_2SiO_5 sources used in geopolymers and can induce the formation of C–S–H alongside the primary N-A-S-H gel network (Xu et al., 2021). Hu et al. (2017) reported that in geopolymers, Si and Al are dissolved from raw materials in an alkaline environment, forming a gel network that later hardens into the geopolymer structure. The presence of Ca^{2+} introduces a competing reaction that forms C–S–H, which is typically seen in ordinary Portland cement. This C–S–H formation can interfere with or alter the extent of traditional geopolymerization. While C–S–H increases early strength, it is less chemically stable in highly alkaline environments compared to N-A-S-H gel. This can affect durability over time, especially in aggressive chemical environments (Lee and Van Deventer, 2004; Mostafa et al., 2014). Zhang et al. (2022) reported that Fe^{2+} or Fe^{3+} impurities can substitute for Al^{3+} in the Al_2SiO_5 network due to their similar ionic sizes. This substitution alters the bonding and cross-linking in the geopolymer network. In some cases, Fe^{2+} or Fe^{3+} can form secondary iron-silicate or iron-aluminate phases, which may coexist with the primary geopolymer matrix, introducing complexity to the material's microstructure. However, Fe^{2+}- or Fe^{3+}-rich geopolymers can exhibit different colors, ranging from brown to red, depending on the iron's oxidation state. The oxidation state may vary during curing due to thermal or environmental factors. It was also found that Fe incorporation into the network can lead to slight changes in mechanical strength. Fe^{2+} or Fe^{3+} Al_2SiO_5 structures are typically more brittle than aluminum-based networks, which might reduce flexural strength. Fe^{3+} can increase the chemical resistance of geopolymers, particularly against acidic environments, but it may also lower mechanical strength (He, 2016; Yao et al., 2016; Zhang et al., 2022). Giroudon et al. (2021) reported that the presence of sulfur triggers the formation of ettringite—particularly in calcium-containing systems—which competes with Al_2SiO_5 gel formation and reduces the extent of geopolymerization. Sulfur, often present in the form of sulfates (SO_4^{2-}), interacts with calcium to form

Table 4
Summary of the effect of curing time on CBG cement.

Reference	Parameter	Short curing time (1–7 days)	Extended curing time (28 days or more)	Effect of curing time
Shubbar et al. (2019)	Water Content & Shrinkage	Faster water loss, higher risk of shrinkage and cracking	Reduced shrinkage, uniform matrix formation.	Extended curing reduces cracking.
Shoaei et al. (2019)	Microstructure	Unreacted or partially reacted clay, higher porosity.	More compact, denser microstructure, reduced porosity.	Dense matrix forms with longer curing
Wang et al. (2020a)	Durability & Chemical Resistance	Limited resistance to chemicals, higher vulnerability.	Improved chemical resistance and environmental durability.	Longer curing enhances durability.
Khalil et al. (2020)	Sustainability	Faster but potentially lower long-term performance.	Longer curing provides better long-term sustainability.	Longer curing enhances material longevity.
Yener (2020)	Compressive Strength	Rapid initial strength gain but incomplete development.	Steady increase in strength, reaching peak performance.	Longer curing improves strength.
Gulec (2023)	Curing Temperature	Ambient curing may delay strength development.	Curing at elevated temperatures accelerates geopolymerization.	Temperature influences curing duration.
Verma et al. (2024)	Mechanical Properties	Strength increased up to 24 h of curing	Strength decreased beyond 24 h	Optimal curing time is 24 h for maximum strength
Pasaribu et al. (2024)	Mechanical Properties (AIV)	AIV decreased from 13.20% to 12.46% over 48 h	AIV increased to 12.94% after 72 h	Optimal strength is achieved at 48 h; extended curing may reduce strength
Kim et al. (2025)	Flexural Strength	Achieved >98% of saturated strength in 6 days at room temperature	Steady increase in strength reaching peak performance.	Rapid strength gains are advantageous for applications

Table 5
An overview of how CBG cement is affected by curing temperature.

Reference	Curing Temperature	Effect on Compressive Strength	Effect on Microstructure	Shrinkage and Cracking	Durability	Setting Time
Xue et al. (2015)	Ambient (20–25 °C)	Slow strength development, takes ~28 days to reach peak.	Porous, less dense initially, but improves over time.	Lower shrinkage but slower setting, longer curing is needed.	Good durability with extended curing.	Long setting time, slow geopolymerization.
Assaedi et al. (2016)	Moderate (40–80 °C)	Fast strength gains within 7 days, higher early strength.	Dense, compact microstructure forms rapidly.	Moderate shrinkage may need controlled moisture curing.	Better durability due to dense structure.	Faster setting time, optimal curing at ~60 °C.
Amran et al. (2021)	High (>100 °C)	Rapid strength gain but risk of microcracking and reduced long-term strength.	Microcracks, reduced density, and increased porosity due to rapid water loss.	Severe shrinkage, high risk of cracking, and defects.	Reduced long-term durability due to cracking.	Extremely fast setting may compromise geopolymerization.
Abdila et al. (2022)	100–120 °C (High Heat)	Rapid strength gains within 24 h, but an early plateau.	Denser structure, but risk of microcracks forming due to rapid water loss.	Moderate shrinkage, microcracks may form in areas of high stress.	Durability is good, but microcracks may reduce long-term performance.	1–2 h. Fast setting time, early hardening may lead to shrinkage.
Metekong et al. (2022)	120–150 °C (Very Hot)	Strength increases quickly but may decrease over time due to cracking.	Dense with more significant microcracks from rapid water evaporation.	High shrinkage; microcracks are more common, leading to weakening.	Durability is compromised by increased microcracks.	30–60 min — Very fast setting, can lead to incomplete geopolymerization.
Lopes et al. (2023)	200+ °C (Excessive Heat)	Rapid strength gains within 24 h, but an early plateau.	Denser structure, but risk of microcracks forming due to rapid water loss.	Moderate shrinkage, microcracks may form in areas of high stress.	Durability is good, but microcracks may reduce long-term performance.	1–2 h. Fast setting time, early hardening may lead to shrinkage.
Bao et al. (2024)	60–90 °C	Early strength significantly improved; 1-day strength up to 80 MPa, 3-day up to 97.5 MPa.	Dense matrix initially; prolonged curing at 90 °C leads to increased porosity and micro-defects.	Prolonged high-temperature curing increases pores and micro-defects due to chemical shrinkage.	Optimal at 60–90 °C for short durations; prolonged high-temperature curing reduces mechanical strength.	Rapid setting at elevated temperatures; prolonged curing may compromise strength.
Siciliano et al. (2024)	50 °C at 20 MPa pressure	Compressive strength improved by 177% compared to ambient curing.	Development of regular nanoporosity; refinement of macropores to micropores.	Excessive temperatures (>100 °C) can cause early cracks due to water evaporation.	Optimal curing conditions (50 °C, 20 MPa) enhance mechanical and morphological characteristics.	Not specified.
Zhan et al. (2025)	40 °C, 60 °C, and 80 °C	Higher early-age compressive strength observed at 60 °C and 80 °C; optimal strength at 60 °C.	Denser microstructure with fewer pores at 60 °C; 80 °C leads to microcracks due to rapid water loss.	Moderate shrinkage at 60 °C; increased shrinkage and cracking at 80 °C.	Better durability at 60 °C due to optimal microstructure; compromised durability at 80 °C.	Faster setting time at elevated temperatures; optimal at 60 °C.

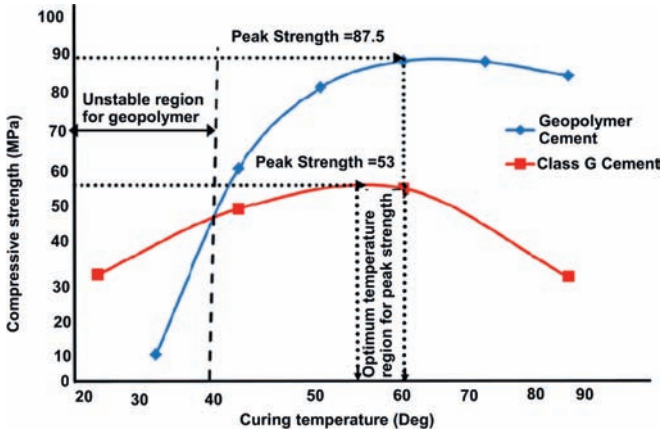


Fig. 9. Graphical illustration of compressive strength against curing temperature on geopolymer cement and class G cement (Sajedi and Razak, 2011).

expansive phases, such as ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}{\cdot}26H_2O$), which can disrupt the geopolymer matrix. In addition, ettringite is an expansive phase, meaning that its formation leads to volume increases, which can cause internal stresses and cracking in the geopolymer structure.

6. CBG application in oil Well cementing

The oil and gas sectors have focused on CBGs because of their unique properties, which include excellent thermal stability, chemical resistance, and environmental friendliness. They offer promising solutions for various applications in drilling, cementing, wastewater treatment, and well completion (Davidovits, 2008; Davoodi et al., 2024; Sadiq et al., 2021; Yahya et al., 2024a, 2024b). The application of CBGs in oil well cementing has been explored over the years, as they offer several advantages over traditional cementing materials. One of the key aspects of CBG use in oil well cementing is their ability to withstand corrosive environments (Castillo et al., 2021; Umunnawuike et al., 2024a, 2024b). The six major types of CBG applications in oil wells are (1) application in aggressive environments, (2) well plug and abandonment, (3) wellbore stability, (4) compatibility with drilling fluids, (5) enhanced sealing and zonal isolation, and (6) enhanced performance under extreme conditions. Fig. 11 shows the process flow diagram of geopolymers in oil well cement construction.

6.1. Application in aggressive environments

CBGs have gained attention as sustainable alternatives to ordinary Portland cement, particularly in aggressive environments characterized by exposure to acidic or saline conditions. Their unique properties, derived from the Al_2SiO_5 structure of clays, make them suitable for applications in which durability and resistance to chemical attack are critical (Khalifeh et al., 2018; Kanesan et al., 2018). CBGs exhibit promising resistance to aggressive environments, particularly in those involving chloride and sulfate exposure. Tuyan et al. (2018) examined calcined lateritic and found that CBG materials maintain their structural integrity when subjected to conditions that typically degrade

Table 6
Condensed information about how particle size affects CBG cement.

Reference	Particle Size (μm)	Effect on Compressive Strength	Effect on Microstructure	Effect on Setting Time	Effect on Workability
Sukmak et al. (2013)	<2 μm (Nanoscale)	Very high early strength due to increased surface area for reaction.	Forms a very dense and compact microstructure with fewer voids.	Accelerated setting time due to rapid reactions.	Reduced workability, higher water demand.
Sumesh et al. (2017)	2–5 μm (Clay-sized)	High early strength, good long-term strength.	Produces a dense matrix with minimal porosity.	Quick setting time, but controllable.	Fair workability, moderate water demand.
Kaze et al. (2018)	>50 μm (Clay-sized)	Very low early strength, poor long-term strength.	Highly porous, weak microstructure with large, connected pores.	Significantly delayed setting time.	Excellent workability, low water demand
Pourabbas et al. (2018)	5–10 μm (Clay-sized)	Moderate early strength, reasonable long-term strength.	Moderately dense structure, some visible pores remain	Moderate setting time.	Good workability, balanced water demand.
Ben et al. (2018)	10–50 μm (Clay-sized)	Lower early strength, delayed strength development.	Porous microstructure with larger voids, affecting strength.	Slower setting time, more controllable.	Good workability, easy to mix and place.
Wang et al. (2021b)	50–100 μm (Clay-sized)	Reduced strength, slow strength development.	Larger voids and unreacted particles increase porosity.	Slow setting time increased handling time.	Good workability, low water demand.
Kaze et al. (2022)	100–200 μm (Clay-sized)	Low compressive strength, significant delay in strength gain.	Highly porous matrix with numerous large voids.	Significantly delayed setting time, manageable.	Improved workability, easy to mix and place.
Migunthanna et al. (2023)	>200 μm (Clay-sized)	Very low strength, poor long-term strength potential.	Extremely porous, high unreacted material, weak matrix.	Very slow setting, risk of incomplete hardening.	Excellent workability, very low water demand.
Das (2024)	15–100 nm (Nano-silica)	Enhanced early compressive strength with optimal nano-silica content; excessive amounts may reduce strength.	Densified microstructure with refined pore structure.	Accelerated setting time with increased nano-silica content.	Optimal workability at 1% nano-silica; higher contents decrease flowability.
Dong et al. (2025)	5–75 μm (Clay-sized)	Compressive strength initially decreases and then increases with increasing particle size.	Microstructure becomes denser with finer particles due to better dissolution and gel formation.	Setting time increases with finer particles.	Workability improves with coarser particles; finer particles reduce fluidity.

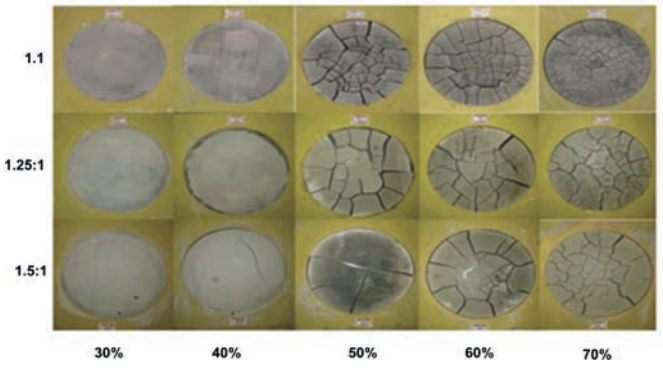


Fig. 10. Shrinking and cracking morphology effect on CBG (Xu et al., 2021).

conventional cement. They reported that geopolymers retain significant strength and exhibit minimal degradation over time. Another key aspect of durability research is the behavior of CBGs under sulfuric acid attack. Al Ani et al. (2024) suggested that geopolymers can withstand a sulfuric acid environment better than traditional cement-based materials can. Degradation is characterized by a distinct layer of altered material, with studies showing that the corrosion depth varies depending on the specification of the clay composition and exposure conditions. The ability to resist acid attack is attributed to the robust bonding network formed throughout the process of geopolymerization, which includes the formation of Si or Al structures that are less susceptible to acid dissolution (Ghani et al., 2022). Pasupathy (2017) used MBGs in a CO_2 environment to test the durability of CBGs. The sample was cured for 3 days and then kept in a CO_2 tank for 15 days at 194 °F and 4000 psi. The geopolymer demonstrated excellent mechanical characteristics, with no discernible degradation found in the microstructural investigation. Fig. 12 shows conventional drilling and drilling with geo-cooler technology in an HPHT oil well.

6.2. Well plug and abandonment

Oil and gas wells are usually plugged using cement and abandoned when they reach the end of their economic limits. A strong cement should prevent leaks, whether temporary or permanent. Ordinary Portland cement is commonly used for this purpose (Chukwuemeka et al., 2023; Khalifeh et al., 2015; Zhang, 2020). However, Portland cement has some drawbacks, such as cement shrinkage, which results in leaks. In Portland systems, the reason for cement shrinkage is gas migration and volume loss of cement during hardening because water is absorbed by hydrated cement products, calcium silicates, and ettringite (Gunasekara, 2019; Quraishi, 2011). CBGs are increasingly recognized as viable alternatives to plug-and-abandon operations in oil well cementing. The geopolymer hardening method is distinct; its properties make it suitable for creating durable barriers that can effectively seal wells and prevent fluid migration, which is crucial for environmental protection and resource management (Manikumar et al., 2024; Somna, 2011). Quraishi (2011) assessed the viability of using CBGs in well-plugging and abandonment tasks and found that kaolinite could be used as the parent material for geopolymers. Yang (2022) provided additional evidence of the use of geopolymers as plug-and-abandon materials. They found that compared to Portland cement, metakaolin clay combined with NaOH and Na_2SiO_3 solution shows reduced shrinkage. The compressive and shear bond strengths of the geopolymer system are also greater. Rahman et al. (2020) reported that CBGs are attractive alternatives to Portland cement, as they can be produced with lower energy input, and they use industrial byproducts or natural clays. This aligns with modern regulations and sustainability goals for decommissioning oil and gas infrastructure, as shown in Fig. 13.

6.3. Wellbore stability

CBGs are used to improve the stability of wellbores because of their mechanical properties and resistance to chemical degradation; these characteristics help maintain the integrity of the well structure, particularly in an environment in which traditional cement may fail due to chemical attacks or physical stresses (Ganesan et al., 2015; Nasvi et al., 2014). The effectiveness of geopolymers in stabilizing wellbores is influenced by various factors, including the chemical composition of precursor materials, water content in the mixture, and curing conditions. Previous studies have emphasized the need for optimization to achieve the best balance between workability and strength development, with the optimal water content being generally below 35 wt% (Giasuddin et al., 2013; Maryoto, 2020). Alvi et al. (2020) noted that in drilling and extracting oil and gas, the wellbore must remain intact during the entire process. Failure of the wellbore can result in structural collapse, expensive repairs, loss of resources, or even environmental disasters. Traditionally, cement-based materials are used to stabilize wellbores, but they can face several issues, such as chemical degradation due to harsh underground conditions, high salinity, and acidity, as well as physical stresses, such as high pressure and temperature variations. This is where geopolymers, such as CBGs, present an advanced solution.

6.4. Compatibility with drilling fluids

Drilling fluids are essential for cooling, lubricating the drill bit, removing the cuttings from the depth of the well to the subsurface, and ensuring wellbore stability. During cementing operations, the compatibility of cement materials with drilling fluids is critical because the cement slurry must displace the drilling fluid while ensuring proper bonding with the wellbore (García-Lodeiro, 2011; Liu et al., 2015; Oseh et al., 2020). Geopolymers, especially CBGs, exhibit excellent compatibility with a variety of drilling fluids. Galindo-Rosales et al. (2011) reported that CBGs are highly compatible with water-based muds, the most common type of drilling fluid, in which water serves as the continuous phase. The interaction between geopolymer slurries and water-based fluids is stable, minimizing the risk of contamination or dilution. Nita et al. (2013) observed that oil-based muds, which use oil as a continuous phase, pose more compatibility challenges for traditional Portland cement. However, CBGs can be tailored with surfactants and chemical additives to ensure good bonding and stable interaction

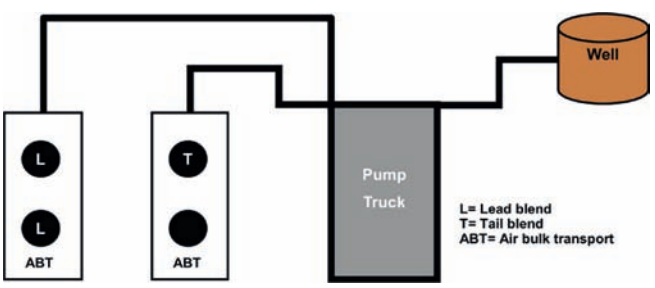


Fig. 11. Process flow diagram of geopolymer in oilwell cement construction (Meade et al., 2023).

with oil-based systems. Synthetic-based drilling fluids, derived from synthetic materials, have properties similar to oil-based muds and are engineered for environmental safety (Money et al., 2025b; Oseh et al., 2022). CBG cement can also interact effectively with these fluids, ensuring a strong cement bond and improved well integrity.

6.5. Enhanced sealing and zonal isolation

One of the primary goals of cementing jobs is to ensure effective zonal isolation, which prevents the migration of fluids (e.g., hydrocarbons, gas, or water) between different geological formations. Failure in zonal isolation can lead to catastrophic events, such as wellbore failure, blowouts, and environmental contamination (Jiang et al., 2010; Khalifeh, 2019; Khalifeh et al., 2015). Li et al. (2024) reported that CBGs can develop compressive strength earlier than Portland cement can, facilitating a faster setting time and thus reducing the waiting period before further drilling operations. Notably, this strength ensures a long-term and stable barrier in the wellbore. Furthermore, the microstructure of CBG materials is denser than that of traditional cement, leading to lower permeability. This reduces the risk of migrating fluid through the cement, improving the overall sealing performance and preventing blowout. CBGs have superior resistance to harsh chemical environments, such as acidic or saline drilling fluids. This makes CBG cement ideal for use in oil wells, in which drilling fluids or downhole conditions may compromise the performance of ordinary Portland cement. A recent investigation by Nuru et al. (2025) found that the rheological characteristics of CBG slurries can be fine-tuned by varying the mix design and additives, such as superplasticizers, to ensure smooth placement and flow behavior. This ensures that the cementing operation proceeds smoothly, preventing issues such as fluid loss, channeling, or poor displacement efficiency. By contrast, Portland cement can generate significant heat during hydration, leading to thermal cracking. Additionally, CBGs have a much lower heat of hydration. This makes them especially suitable for deep oil wells, in which the exothermic reaction of traditional cement could cause damaging stress on the casing or formation. Fig. 14 demonstrates different well design concepts for deep oil wells. In oil wells, the casings must be fully cemented to minimize casing expansion, especially during steam production, and to prevent buckling.

6.6. Enhanced performance under extreme conditions

Wells drilled into deep or high-temperature formations place additional demands on cement materials. CBGs exhibit excellent performance characteristics under these extreme conditions (Medeiros and Helene, 2009). The essential thermal stability, low permeability, and chemical resistance of CBGs make them excellent candidates for maintaining structural integrity under harsh conditions. A laboratory investigation carried out by Wang et al. (2019b) showed that ordinary Portland cement can degrade at temperatures above 300 °F (150 °C). By contrast, CBGs maintain their integrity and strength at temperatures up to 1500 °F (815 °C). This makes them ideal for high-temperature geothermal wells or HPHT conditions in oil and gas wells. The structural characteristics of CBGs give them superior resistance to deformation under high pressure, making them highly effective in ensuring wellbore integrity in high-pressure environments. Tracy et al. (2018) argued that one of the common problems with traditional cement is shrinkage during the hydration process, which can lead to microannuli (small gaps) between the cement and the well casing. However, CBG cement exhibits negligible shrinkage, leading to better bonding with the well casing and intact formation in field tests. Wang et al. (2020b) highlighted that geopolymer-based cementing systems have shown improved bonding and stability in HPHT wells, in which traditional cement often suffers from performance issues, such as gas migration or premature failure. Field trials in offshore and onshore wells have demonstrated that CBGs can be seamlessly used with a range of drilling fluids, from water-based muds in shallow wells to synthetic-based muds in deepwater drilling. In a study in Oman, geopolymer cement for HPHT conditions was used (Salazar et al., 2024). The flowability test showed that good flowing behavior facilitated efficient bulking and blend delivery to the mixing system in the cementing process. Table 7 shows the application of CBGs in oil and gas well cementing operations.

6.7. Cementing of liner strings

CBGs customized for downhole temperature and pressure conditions can be successfully introduced to oil field well construction.

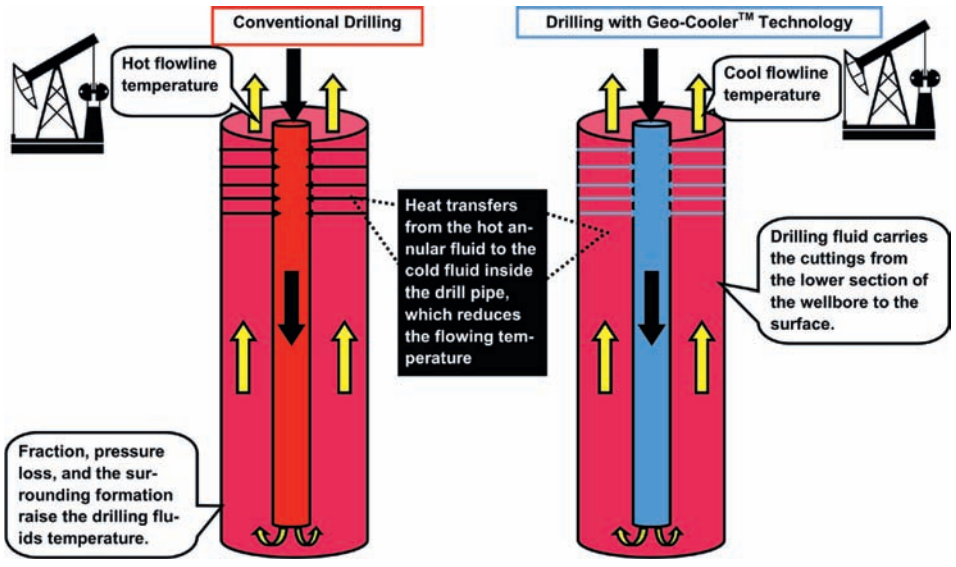


Fig. 12. High temperature, high pressure in an oil well using (a) conventional drilling, (b) drilling with geo-cooler technology.

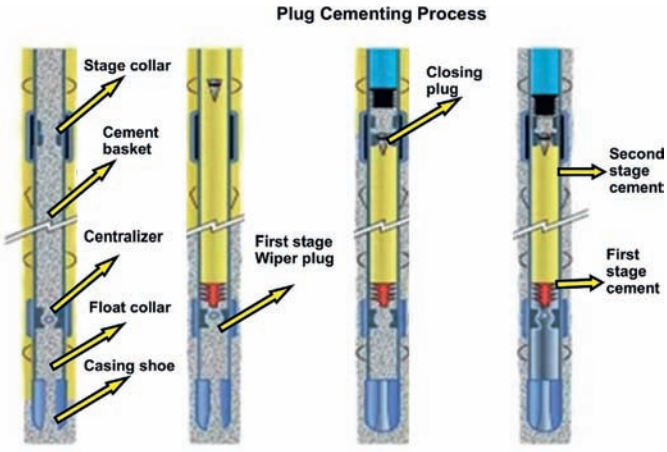


Fig. 13. Well plug-in and abandonment (Rahman et al., 2020).

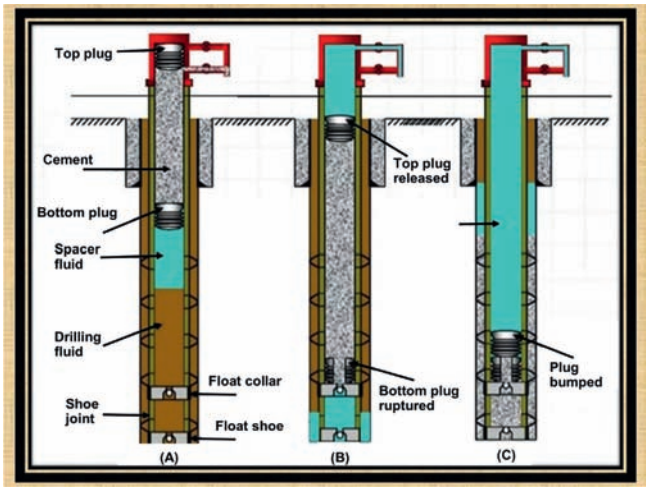


Fig. 14. illustrates the effectiveness of CBG cement in sealing and zonal isolation during oil well cementing operations.

For instance, geopolymer cement was specifically used for the primary cementing of liner strings in the Persian Basin (Meade et al., 2023). The results demonstrated that geopolymer cementing can fit into the oil field cementing workflow without major changes to the job design process, on-site execution, or post-job evaluation. The post-job pressure matched hydraulic simulations versus the recorded pressure during the job execution, confirming proper placement (Fig. 15). Conventional sonic and ultrasound cement bond logging tools also confirmed the presence of geopolymers within the wellbore, providing further assurance, and the geopolymer was compatible with conventional cement on similar wells.

7. Challenges and prospects

CBGs also present several application challenges, particularly in oil well cementing, construction, and environmental management. In recent years, these difficulties have been a topic of interest in the literature, with a focus on addressing various obstacles to the widespread adoption and optimization of such materials. These challenges are (1) the variability of raw materials, (2) workability issues, (3) alkaline activator challenges, (4) short thickening time, and (5) sudden temperature increases.

7.1. Variability of raw materials

The variability of raw materials, particularly in CBGs, directly affects the mechanical properties and suitability of the final product (Jabbour et al., 2022). Factors such as mineral composition, particle size distribution, and impurities can cause significant differences in strength, durability, and setting time, which are all crucial in oil well cementing, construction, and environmental remediation. The use of different clay minerals, such as kaolinite, illite, and montmorillonite, leads to variations in chemical composition, affecting the availability of Al and Si necessary for geopolymer formation (Abdullah et al., 2018; Tahmasebi et al., 2021; Chen et al., 2010). Furthermore, different activator types and concentrations can alter the rates at which Si and Al dissolve in raw materials, leading to polymerization inconsistencies and affecting setting times and mechanical properties. Understanding and controlling these factors enable geopolymer formulations to be tailored to meet the performance criteria specific to each application. In oil well cementing, for instance, high-temperature stability and resistance to sulfate attack are prioritized, while in construction, early strength development and workability are often key considerations.

7.2. Workability issues

CBGs typically exhibit high viscosity and stickiness, making mixing and application difficult, as the layered structure of clay particles leads to increased interparticle friction. To improve flowability, excess water is often added, which compromises the mechanical strength of the final products (Janas et al., 2013; Nematollahi and Sanjayan, 2014; Yaseri, 2017). Therefore, achieving uniform compaction is challenging, potentially resulting in weak structures if not properly executed. NaOH or KOH can affect both workability and mechanical properties. However, high concentrations may lead to reduced workability due to increased viscosity, while low concentrations may improve flowability but could compromise geopolymer strength. To address this issue, superplasticizers can help improve flowability by dispersing clay particles, reducing interparticle friction, and allowing for a lower water content (Li et al., 2022). In addition, pre-treating or modifying clay particles can reduce the effect of their layered structure on viscosity. Thermal or chemical treatments can partially dehydroxylate the clay and enhance its dispersion in the matrix.

7.3. Alkali activator challenges

Alkali activators in CBGs are crucial for initiating geopolymerization; however, they present several challenges that can affect the performance and workability of the final product (Bature et al., 2021; Nath and Sarker, 2014). Alkali activators, especially Na_2SiO_3, can increase the viscosity of the mix, making it difficult to achieve the desired workability (Li et al., 2022). Furthermore, alkali-activated CBGs can have a quick setting time, which reduces the working window for mixing, placing, and finishing (Caselles et al., 2023). Excess alkali ions can migrate to the surface, resulting in efflorescence, which affects aesthetics and indicates leaching. Slightly diluting the activator with water can reduce viscosity but requires careful balancing to avoid excess water that might weaken the final product. Using a combination of NaOH and KOH can sometimes result in lower viscosity while maintaining reactivity. Adding retarding agents, such as citric acid or tartaric acid, in controlled amounts can also slow down the reaction rate, giving more time for handling.

7.4. Short thickening time

A short thickening time is a critical challenge that influences the application of CBG cement, particularly in the oil well cementing process. It can lead to challenges in cement placement and performance, while an excessively long thickening time may hinder operational efficiency (Bowerman et al., 2013; Malley et al., 2023; Yan et al., 2024). Indeed, thickening time is a major factor to be considered for CBG cement, especially in oil well cementing, in which precise timing is essential. A thickening time that is too short can cause early gelation, making it difficult to properly place the cement into the wellbore, which risks compromising the integrity of the cement sheath. This issue can be exacerbated by downhole conditions, such as high temperatures and pressures, which may further accelerate the setting time (Salehi et al., 2016). By contrast, if the thickening time is overly prolonged, operational processes are delayed, potentially extending the time the well is left without adequate support and increasing the costs and risks associated with a prolonged rig time. Therefore, achieving an optimal thickening time, which requires a balance between rapid strength development and operational feasibility, is critical. To address this issue, additives or curing conditions, such as temperature or alkaline activator concentration, may be adjusted to modify the thickening time for CBG cement, helping to tailor its properties to specific well conditions.

7.5. Sudden increase in temperature

The effect of sudden increases in temperature on CBG materials is a significant obstacle that the operation of oil and gas cementing faces today, especially in high-temperature

Table 7
Previous studies on the different types of clay geopolymers and their synthesis method, mechanism, and application.

Reference	Types of Clay	Synthesis Method	Reaction Mechanism	Findings	Application
Muñoz et al. (2012)	Kaolinite	Sodium hydroxide activation, cured at 40 °C	Dissolution, gelation, and hardening	Good mechanical properties, chemical resistance	Construction materials, waste containment
Song et al. (2014)	Kaolinite with illite	Alkali activation, curing at 40 °C	Dissolution, polymerization	Enhanced resistance to freeze-thaw cycles, sulfate resistance	Durable construction, infrastructure
Khalifeh et al. (2015)	illite	Alkali activation, curing at low temperature	Polycondensation of aluminosilicates	Enhanced mechanical strength, good thermal stability	Repair materials, precast elements
Nasvi et al. (2016)	Kaolinite with illite	Alkali-thermal activation of clays	Si and Al species polymerization	High early-age strength, excellent durability	Precast concrete, structural components
Longhi et al. (2019)	Montmorillonite	Activation with sodium silicate and NaOH	Si–*O*–Al network formation	Enhanced mechanical properties, reduced CO_2 emissions	Sustainable construction materials
Wang et al. (2019b)	Low-grade Kaolinite	Alkali activation of low-grade clays	Dissolution, polycondensation	Enhanced mechanical strength, reduced water absorption	Paving blocks, tiles, and eco-friendly cement
Wang (2020a)	Kaolinite	One-part geopolymer synthesis	In-situ polymerization	Simplified manufacturing process, cost-effective	Industrial waste recycling, building materials
Jindal and Sharma (2020)	Halloysite	Geopolymerization at ambient temperature	Formation of amorphous to semi-crystalline phases	Improved durability, environmental benefits	Infrastructure, environmental applications
Freire (2020)	Kaolinite	Alkali activation	Dissolution of aluminosilicates, gelation	Improved thermal and acoustic insulation properties	Construction materials, insulation
Wang, 2020b	Kaolinite with Montmorillonite	Alkali-thermal activation of clays	Si and Al species polymerization	High early-age strength, excellent durability	Precast concrete, structural components
Raganati et al. (2021)	Kaolinite	Ambient curing, fly ash, and kaolinite mix	Geopolymer gel formation	Low thermal conductivity, good fire resistance	Thermal insulators, fireproof panels
Prałat (2022)	Halloysite	Alkali activation, curing at ambient temperature	Geopolymerization	Enhanced mechanical properties, good workability	Paving blocks, bricks, and eco-friendly cement
Tian (2020)	Kaolinite	Alkali activation, microwave curing	Accelerated dissolution and gelation	Rapid strength gain, energy-efficient process	Rapid construction, precast elements
Hou et al. (2022)	Halloysite	Activation with sodium silicate and NaOH	Si–*O*–Al network formation	Improved durability, environmental benefits	Sustainable construction materials
Adjei et al. (2022)	Kaolinite	One-part geopolymer synthesis	In-situ polymerization	Simplified manufacturing process, cost-effective	Industrial waste recycling, building materials
Liu et al. (2024)	Kaolinite	Ambient curing, fly ash, and kaolinite mix	Geopolymer gel formation	Low thermal conductivity, good fire resistance	Thermal insulators, fireproof panels
Mahmoud et al. (2024)	Halloysite	Metakaolin and waste clay activation	Alkaline activation and polymerization	High resistance to freeze-thaw cycles, sulfate resistance	Durable construction, infrastructure
Samadi et al. (2024)	Kaolinite	Activation with sodium silicate and NaOH	Polymerization of Si and Al species	High compressive strength, low water absorption	Building materials, lightweight panels
Zou et al. (2024)	illite	Alkali activation, microwave curing	Accelerated dissolution and gelation	Rapid strength gain, reduced curing time	Rapid construction, precast elements
Khan et al. (2025)	Kaolinite with EFBA	Alkali activation using NaOH and sodium silicate, curing at 60 °C	Dissolution, polycondensation, and gelation	Compressive strength >40 MPa, good thermal stability	Oil well cementing, high-performance geopolymer binder
Money et al. (2025a)	Kuala Rompin Clay (KRC)	Alkaline activation with EFBA, varying KOH molarity	Dissolution of aluminosilicates, gel formation	High compressive strength (>40 MPa); improved microstructure; increased strength with KOH molarity	Oil well cementing, high-performance geopolymer cement

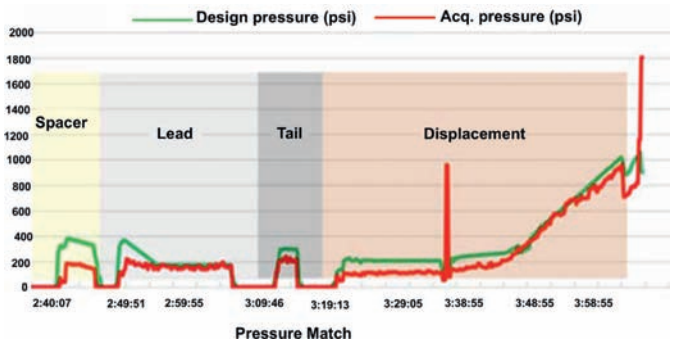


Fig. 15. Post-job pressure match from intermediate liner job (Meade et al., 2023).

environments. When CBGs are subjected to sudden temperature increases, significant microstructural alterations are bound to occur (Zhang et al., 2024; Fu et al., 2024a, 2024b). The primary binding phase that gives strength to CBGs is the C–S–H gel. Abrupt temperature changes have the potential to affect C–S–H stability negatively. New mineral phases, such as CH or various Si minerals, may form, affecting grout durability and mechanical properties (Mucsi et al., 2019). Samadi et al. (2024) indicated that exposure to elevated temperatures within the geopolymer matrix can cause the development of new crystalline phases. For instance, MBGs cured at lower temperatures (around 163 °F) and then rapidly exposed to higher temperatures (up to 248 °F) lead to the development of crystalline structures, such as gobbinsite and anorthite. These changes can induce thermal stress within the material, potentially weakening its integrity and reducing its effectiveness as a sealing material in oil well cementing. Mitigating these effects often involves adjusting the formulation of CBGs, such as incorporating additives that enhance thermal stability, optimizing the curing process, or applying post-curing heat treatments to improve resistance to thermal shock. Furthermore, implementing a controlled curing process with a gradual temperature increase helps CBGs form a denser, more thermally stable structure. A combination of ambient and elevated-temperature curing (curing at 80°C-100 °C) can enhance a material's resistance to thermal shocks.

7.6. Uneven agreement of data

Significant variations in experimental results using clay geopolymers for oil well cement applications highlight the complexities of the material. For example, Adjei et al. (2022) reported the presence of new crystalline phases, such as gobbinite and anorthite, when metakaolin is cured at 163 °F. They concluded that the presence of the crystalline phase has the potential to cause thermal stress, weaken the system, and impair its ability to effectively isolate formation and support the casing. By contrast, Patrick et al. (2024) reported that metakaolin has 70.73% amorphous phases, based on X-ray diffraction results, suggesting the presence of irregular and nonrepeating atomic structures after 28 days of curing at 70 °C and 90 °C. The results of the AFM analysis further demonstrated that the geopolymer pastes are free of cracks and contain few pores, indicating the existence of amorphous phases. Some studies have also reported improved mechanical properties and durability with CBGs, while others have identified degradation and issues with wellbore conditions. Khalifeh et al. (2015) simulated the performance of geopolymers at downhole conditions of 1000 psi and 87 °C. They reported that geopolymers have favorable compressive strength, viscosity, consistency, permeability, and shrinkage. Miao et al. (2023) found that under 150 °C hydrothermal conditions, the strength of pure metakaolin geopolymers sharply decreases, with a reduction rate of 81.8% compared to a sample subjected to 150 °C drying conditions. By contrast, the strength of metakaolin-cement geopolymers is generally stable, with only a slight decrease of 14.4%. To address strength reduction, the performance of CBGs can be enhanced by incorporating nanoparticles. Nanomaterial-based geopolymers have better mechanical properties and setting times than neat geopolymers. The addition of nanomaterials can produce a more ductile structure with higher compressive and tensile strengths (Alvi et al., 2020).

8. Conclusions

This study presented important information on the status and application of CBGs in the HPHT oil well cementing process. The results, prospects, and challenges encountered in applying CBGs to HPHT oil wells were examined. The following conclusions were drawn from the literature reviewed.

- The wet method is more suitable for laboratory experiments due to its precise control of activators, whereas the dry method is better suited for commercial and field applications of CBGs. For oil well cementing, the dry mixing formulation method is preferable, as it can increase the compressive strength of cement.
- CBGs have a lower carbon footprint than conventional Portland cement, which is used in the drilling sector. In addition, CBGs exhibit lower shrinkage during curing, which helps minimize cracking and deformation, making them more compatible with other additives used in oil well cementing, such as retarders, dispersants, and fluid loss additives.
- Chemical reactivity, dissolution, gelation, polymerization, and growth are the dominant reaction mechanisms of CBGs.
- CBGs can resist acid attack, which is attributed to the robust bonding network formed during geopolymerization.
- Geopolymers exhibit better strength in saline water than in normal water due to their porous systems and the presence of reacted phases. They are appropriate for harsh reservoir conditions because the greater reactivity between the brine and the geopolymer, which occurs at high brine concentrations, prevents alkali leaching and strength deterioration.
- The experimental results showed that the geopolymer system expands by 0.05% and 0.15% after 1 and 18 days, respectively, compared to 0.03% and 0.07% for Portland cement. The self-expanding nature of geopolymers in water indicates that shrinkage can be avoided without the use of a chemical agent.
- Portland cement can degrade at temperatures above 300 °F (150 °C), while CBGs maintain their integrity and strength at temperatures up to 1500 °F (815 °C). This high-temperature stability makes them ideal for geothermal wells. The structural characteristics of CBGs give them superior resistance to deformation under high pressure, making them highly effective in ensuring wellbore integrity in high-pressure environments.
- CBGs are ready for large-scale on-site deployment, as they have been proven to possess the necessary properties for well integrity, are compatible with existing cementing equipment, and demonstrate thermal and mechanical stability under HPHT conditions.

CRediT authorship contribution statement

Barima Money: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rayan Hassan Modather:** Project

administration. **David Abutu:** Formal analysis. **Norasyikin Ismail:** Visualization, Project administration. **Augustine Agi:** Visualization, Validation, Resources, Methodology, Funding acquisition, Conceptualization. **Francis Nyah:** Software, Formal analysis, Data curation. **Siti Qurratu' Aini Mahat:** Visualization, Validation, Supervision, Resources.

Data availability statement

Data will be made available upon request.

Declaration of competing interest

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

Acknowledgement

This work was supported by the Ministry of Higher Education, Malaysia and Universiti Malaysia Pahang Al-Sultan Abdullah through research grants RDU 220375 and RDU 233305.

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