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Review of Fly Ash-Based Zero-Cement Concrete Performance

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Abstract

The urgent need to reduce the environmental impact of construction materials has led to increasing interest in sustainable alternatives to Ordinary Portland Cement (OPC). Among emerging solutions, Zero-Cement Concrete (ZCC) utilizing fly ash (FA) as a primary binder offers a viable pathway for lowering CO_2 emissions and reusing industrial by-products. This review investigates the key components, mixing mechanisms, curing conditions, and mechanical performance of FA-based ZCC. FA, particularly Class F and Class C, in combination with alkaline activators such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), plays a crucial role in the geopolymerization process that forms the cementitious matrix. The compressive strength, modulus of elasticity, and flexural strength of ZCC are influenced by multiple factors, including activator molarity, SS/SH ratio, binder-aggregate proportions, and curing regime. Experimental studies indicate that with optimized mixing and curing parameters, FA–ZCC can achieve mechanical performance comparable to or exceeding OPC concrete. However, the absence of standardized mix design procedures and field-curing strategies remains a challenge. This study highlights the need for further research on durability, life-cycle assessment, and in-situ applications to fully realize the potential of ZCC as a mainstream, eco-efficient construction material.

Keywords: Zero-Cement Concrete (ZCC), Fly ash (FA), Alkali-activated binder, Geopolymer, Sustainable construction.

INTRODUCTION

Concrete remains the most extensively utilized construction material worldwide, with an estimated annual production of approximately 25 billion tonnes [1], [2]]. Since the invention of Ordinary Portland Cement (OPC) by Joseph Aspdin in 1824, it has served as the predominant binder in concrete due to its superior mechanical properties and ease of production [3]. However, OPC manufacturing is highly energy-intensive and has profound environmental implications. The cement production process accounts for approximately 7% to 8% of global carbon dioxide (CO_2) emissions, contributing nearly 1.5 gigatonnes of CO_2 annually [4], [5].

The widespread use of OPC in construction raises concerns due to its significant carbon footprint and its vulnerability to chemical attacks and long-term degradation. These drawbacks have prompted researchers and industry practitioners to explore alternative binder materials, including silica fume, fly ash (FA), and ground granulated blast furnace slag (GGBFS) [6], [7]. These supplementary materials, often sourced as industrial by-products or from natural pozzolanic origins, offer a pathway toward more sustainable concrete production [5]. This transition aligns with the construction sector's broader objective of reducing reliance on carbon-intensive materials and advancing green infrastructure initiatives.

A promising innovation in sustainable construction is Zero-Cement Concrete (ZCC), a class of concrete that completely eliminates OPC. Instead, ZCC employs alternative binders activated by alkaline solutions, forming a matrix with mechanical and durability properties comparable to those of OPC-based concrete while significantly reducing CO_2 emissions. Studies indicate that ZCC can achieve carbon emission reductions ranging from 50% to 80% compared to conventional OPC systems [8]. Despite the growing interest in ZCC, research on cement-free concrete remains in its developmental stages, necessitating further investigation into its long-term performance and practical applications [9].

ZCC has been successfully implemented in various structural and non-structural applications, including bridge decks, boat ramps, pavements, retaining walls, and water tanks [10]. The production of ZCC involves activating aluminosilicate-rich precursor materials using alkaline solutions, typically comprising sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), or alternatively, potassium hydroxide (KOH) and potassium silicate (K_2SiO_3) [7]. This chemical activation facilitates the formation of calcium silicate hydrate (C-S-H) gels, which are structurally and functionally analogous to the hydration products in OPC-based concrete [10]. In existing literature, terms such as alkali-activated materials (AAMs) and geopolymers (GPs) are frequently used, often interchangeably, to describe OPC-free binders [11], [12]. However, distinctions exist in their reaction mechanisms and material compositions. Provis et al. [13] differentiate AAMs as materials typically possessing higher calcium content, whereas geopolymers are generally derived from low-calcium precursors, such as Class F fly ash. Ahmad et al. [14] define ZCC as an advanced geopolymer concrete system where thermal curing is replaced by chemical activation using NaOH and Na_2SiO_3. Nonetheless, the terminology surrounding these systems remains a subject of ongoing debate. Davidovits et al. [15] caution against the indiscriminate use of the term "alkali-activated," arguing that it may lead to misconceptions regarding the fundamental nature of geopolymer concrete.

SIGNIFICANCE OF THE STUDY

The aim of this research is to evaluate the performance of Fly Ash-Based Zero-Cement Concrete (FA–ZCC) as a sustainable alternative to Ordinary Portland Cement (OPC) concrete. By utilizing fly ash as the primary binder and activating it with alkaline solutions, FA–ZCC offers a promising solution to reduce CO_2 emissions and repurpose industrial by-products. This study examines the key factors influencing its mechanical properties, including mix proportions, activator molarity, and curing conditions, while highlighting the challenges related to standardization and large-scale implementation. The findings contribute to the advancement of eco-friendly construction materials, emphasizing the need for further research on durability and practical applications.

METHOD

In preparing this review, a systematic literature review approach was adopted to ensure that the evaluation of fly ash-based zero-cement concrete was comprehensive, transparent, and reliable. This method was selected because it provides a structured process for collecting, screening, and synthesizing previous studies, which helps reduce bias and ensures that the most relevant findings are considered. To gather the necessary information, the search was carried out across several academic databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar. Keywords such as *fly ash geopolymer concrete*, *zero-cement concrete*, *alkali-activated fly ash binder*, and *sustainable concrete materials* were used to identify suitable studies. In addition to these keyword searches, supporting techniques were applied, such as reviewing subject-specific journal issues, tracing references in key articles, and examining highly cited experimental works related to mix design, curing, and mechanical performance.

The selection of sources followed clear inclusion and exclusion criteria. Only peer-reviewed journal articles, conference papers, and technical reports published between 1999 and 2024 were considered, while studies that did not provide quantitative results or that focused on applications of fly ash outside construction were excluded. This process allowed the review to focus directly on the evidence most relevant to the performance and potential applications of fly ash-based zero-cement concrete. After careful screening, around seventy to seventy-five references were included. This number was determined to be sufficient to capture both the breadth of research on chemical composition, mix design, curing, and mechanical performance, as well as the depth required for critical evaluation and practical recommendations.

Once the references were selected, they were examined in detail and organized according to recurring themes and patterns. The analysis was structured around several key aspects: the chemical and physical characteristics of fly ash, proportioning and mix design methods, mixing and curing procedures, mechanical properties such as compressive strength and modulus of elasticity, and durability under different environmental conditions. By identifying similarities and differences across the literature, the review was able to highlight both the strengths of fly ash as a sustainable binder and the remaining challenges that must be addressed for large-scale applications. In this way, the chosen method provided a strong basis for evaluating the performance of fly ash-based zero-cement concrete and for developing recommendations that support its use in sustainable construction.

RESULT AND DISCUSSION

COMPONENTS OF ZERO-CEMENT CONCRETE

Zero-Cement Concrete (ZCC) represents a significant advancement in sustainable construction, offering an eco-friendly alternative to Ordinary Portland Cement (OPC)-based concrete (see Figure 1). As illustrated in Figure 2, the primary constituents of ZCC include a precursor or binder material, usually an aluminosilicate-rich substance such as fly ash (FA); alkaline activators like a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), or potassium hydroxide (KOH) with potassium silicate (K_2SiO_3); aggregates (both fine and coarse); water (potable, distilled, or deionized); and chemical admixtures such as superplasticizers when necessary. Among these, FA and ground granulated blast furnace slag (GGBFS) are the most commonly utilized precursors due to their high reactivity and favorable mechanical and environmental performance [16].

The selection of binder materials is typically based on their abundance, cost, intended structural application, and local availability. These binders are generally derived from natural or industrial by-products rich in aluminosilicate minerals [17]. The alkaline activators are synthesized using alkali metal-based compounds, primarily sodium or potassium. Additionally, superplasticizers (SPs) may be incorporated into the mix to enhance flowability and workability [18]. Experimental data have shown that SP dosages ranging from 0.8% to 1.5% of the total binder content are effective in optimizing fresh-state properties of ZCC [19].

Binders and Alkaline Activators

ZCC relies on a broad range of aluminosilicate materials as precursors, including FA, GGBFS, metakaolin, calcined clays, volcanic ash, boiler ash, silica fume, and other pozzolanic sources [20]. FA and GGBFS are the most widely adopted for geopolymer production due to their superior performance [16]. Metakaolin offers controlled Si/Al ratios due to its high solubility in alkaline environments but requires energy-intensive calcination at 500–700°C, making it relatively expensive [21]. In contrast, industrial by-products such as FA are economically favorable and widely available, contributing to sustainable material cycles [22].

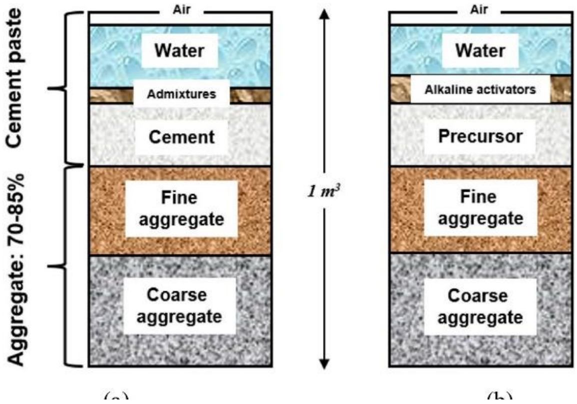

Figure 1. Comparison between [23]: (a) Conventional cement concrete and (b) Zero cement concrete

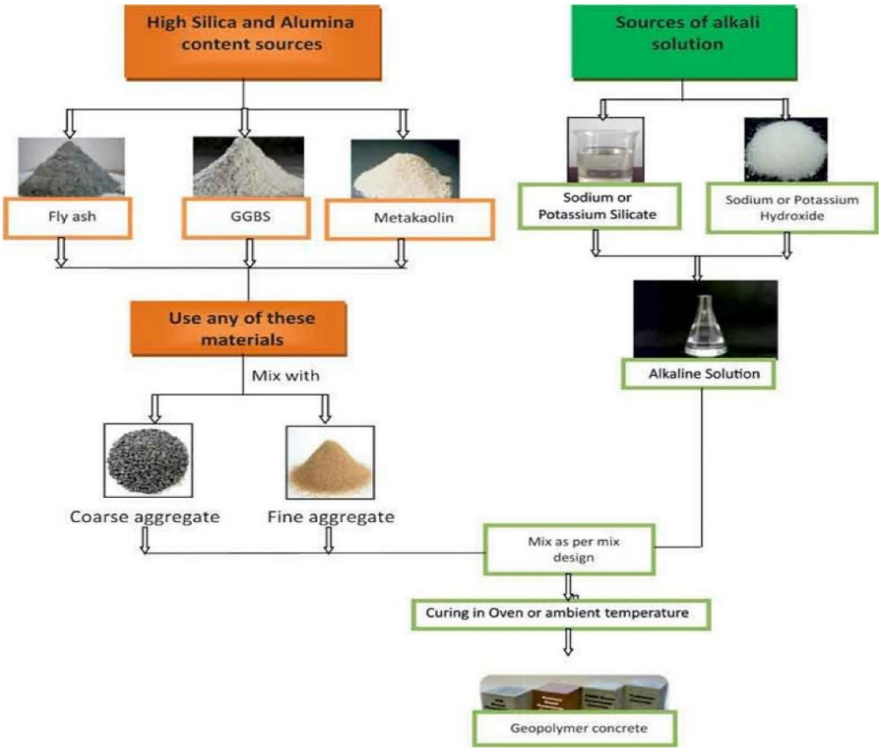

Figure 2. Example of $ZCC's$ components (modified from [24])

Fly ash is categorized into two primary types—Class C and Class F—according to ASTM C618 and AASHTO M295 standards, determined using X-ray fluorescence (XRF) analysis [25]. Class C

FA contains a high proportion of calcium (usually above 20%), whereas Class F is primarily siliceous [26]. Despite its advantages, FA is considered hazardous due to its acidic and toxic constituents, posing risks to human health and the environment [27]. Improper disposal into aquatic environments can lead to severe ecological damage. Globally, FA production stands at approximately 900 million tonnes annually, with China accounting for around 500 Mt, India 140 Mt, the USA and the EU 115 Mt combined, and Australia 14.5 Mt. This production is projected to reach 2 billion tonnes soon [28]. In Table 1, the chemical composition of fly ash derived from different coal sources—bituminous, sub-bituminous, and lignite—is presented. The table highlights the variations in key oxides, including SiO_2, Al_2O_3, Fe_2O_3, CaO, and others, which influence the properties of fly ash in concrete applications. The composition differences among these coal types affect the reactivity and suitability of fly ash for high-strength concrete mix designs.

Table 1. Chemical Composition of Fly Ash from Different Coal Sources (Bituminous, Sub-bituminous, and Lignite)

Component	Bituminous (%)	Sub-bituminous (%)	Lignite (%)
SiO_2	20–60	40–60	15–45
Al_2O_3	5–35	20–30	10–25
Fe_2O_3	10–40	4–10	4–15
CaO	1–12	5–30	15–40
MgO	0–5	1–6	3–1
SO_3	0–4	0–2	0–10
Na_2O	0–4	0–2	0–6
K_2O	0–3	0–4	0–4
LOI	0–15	0–3	0–5

The chemical activation of ZCC binders is facilitated using alkaline solutions, typically composed of Na_2SiO_3 (sodium silicate) combined with NaOH (sodium hydroxide), or K_2SiO_3 (potassium silicate) with KOH (potassium hydroxide) [30]. In some cases, other activators such as calcium hydroxide [$Ca(OH)_2$], magnesium oxide (MgO), and calcium oxide (CaO) may be used depending on mix design requirements [29]. Studies have shown that the mixture of SH and SS results in the highest compressive strength compared to other activation systems [30]. The sodium silicate modulus (SiO_2/Na_2O) plays a crucial role in reaction kinetics, with an optimal ratio of 1.5 promoting effective polymerization [24]. The ratio of alkaline solution to precursor (Alk/FA) significantly affects ZCC performance, with lower Alk/FA ratios associated with higher compressive strength and improved impermeability [31]. Figure 3 representation of the oxide compositions of Class C and Class F fly ashes compared to rapid set cement, highlighting variations in SiO_2, Al_2O_3, Fe_2O_3, CaO, and other key components.

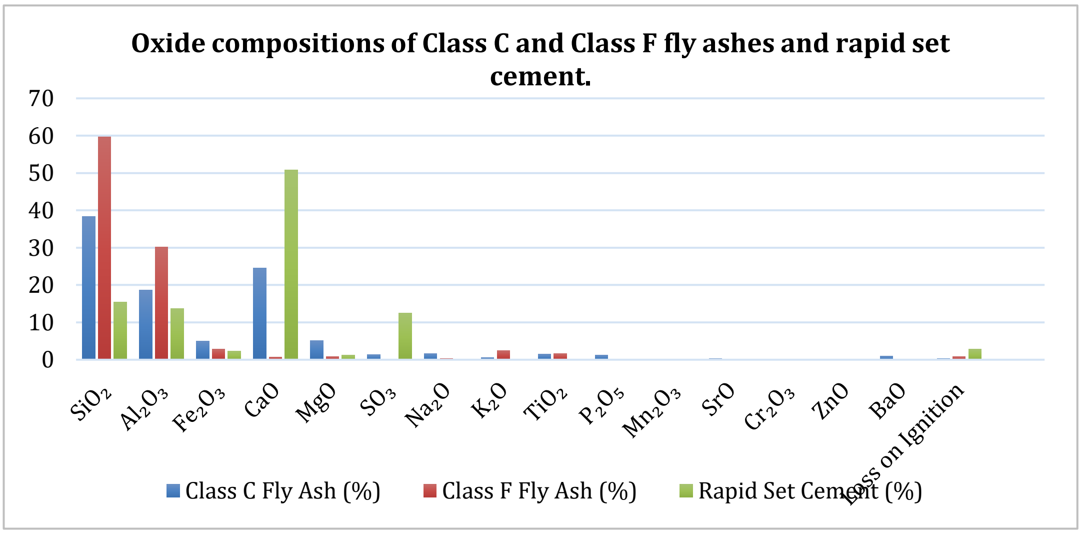

Figure 3. Oxide compositions of Class C and Class F fly ashes and rapid set cement.

Molarity and Mixing Parameters

Sodium hydroxide is commercially available in flake or pellet form, with purity levels ranging from 96% to 98.6%, influencing its price. Sodium silicate (SS), or water glass, is usually sold in gel form, with an optimal SiO_2/Na_2O modulus ratio between 1.0 and 1.5 for practical applications . It is recommended that the alkaline solution be prepared at least 24 hours before use to ensure homogeneity and adequate mixing . The exothermic reaction generated during NaOH dissolution and its subsequent mixing with SS facilitates early polymerization. However, the prepared solution should be used within 36 hours to avoid solidification [23].

Increasing the molarity of SH enhances ZCC's compressive strength, though it may reduce workability [32]. Optimal strength is achieved when the SH molarity ranges between 10M and 16M, with an SS/SH ratio between 0.5 and 2.5 [33], [34]. Workability decreases when the SS/SH ratio exceeds 1.0 or SH molarity rises above 15M. Experimental results indicate that geopolymer concrete can achieve strengths of 60–70 MPa with SH molarity levels of 10M to 15M and an SS/SH ratio of approximately 1.0 [39]. Class F FA mixes showed the highest strength when activated using 15M SH and SS/SH ratios of 1.0 and 2.0. Additionally, increasing SH molarity reduces setting time and flowability, particularly for SS/SH ratios around 1.0 [40]. Despite these trends, the mass ratio of Alk/FA has been found to have minimal effect on compressive strength in some cases [32].

MIXTURE PROPORTION DESIGN

Unlike conventional Ordinary Portland Cement (OPC) concrete, which follows standardized guidelines such as ACI 111.1 for mixture proportioning[28], Zero-Cement Concrete (ZCC) lacks a universally accepted mix design methodology. This absence is attributed to the variability of materials and chemical reactions in ZCC systems, resulting in a reliance on empirical approaches rather than standardized procedures.

Arun et al. [23] conducted a comprehensive review of existing literature on ZCC and geopolymer mix proportioning techniques. Their analysis revealed that most available approaches are based on empirical trial-and-error procedures. Three main strategies were identified: the Target Strength Method, which focuses on achieving a desired compressive strength by fixing the quantity of either the binder or the mixing water; the Performance-Based Method, which adjusts mix proportions based on specific mechanical or durability performance targets; and the Statistical Factorial Design Method, which includes techniques such as the Taguchi method and multivariate regression analysis for optimizing multiple parameters simultaneously.

Among these approaches, the Target Strength Method was found to be the most applied due to its practicality and ease of implementation. However, the authors emphasized that the selection of the most suitable mix design procedure should be governed by the intended application, performance requirements, and available materials [35].

MIXING PROCEDURE

At present, there is no universally standardized protocol for the mixing of Zero-Cement Concrete (ZCC) [36]. Due to the complex chemical interactions inherent in alkali-activated systems, researchers have predominantly relied on empirical approaches, employing trial-and-error methods to determine optimal mixing sequences. Various studies have explored the impact of different mixing protocols on the fresh and hardened properties of ZCC, particularly emphasizing the sequence of material addition and the duration of mixing. A summary of key findings is presented in Table 2.

Behera et al. [37]] conducted an extensive experimental study to optimize the mix design of ZCC mortars by evaluating multiple mixing strategies. Their research investigated four distinct mixing procedures for Class C fly ash (FA) mortars and eight procedures for Class F FA-based ZCCs incorporating varying calcium oxide (CaO) contents. This comprehensive study resulted in the production of 215 and 80 mixtures, respectively. The specific steps for each mixing procedure are detailed in Table 3. Table 3A presents the mixing procedures for Zero-Cement Concrete (ZCC) using Class C fly ash (FA) as the primary binder. It details the sequential addition of coarse aggregate (CA), sand, FA, alkaline activator solution (AAS), and water (Wt), along with the corresponding mixing times for each trial. The variations in mixing sequences aim to optimize the homogeneity and performance of the ZCC mixture. Table 3B outlines the mixing procedures for ZCC mortar, also based on Class C FA. It specifies the stepwise incorporation of FA, sand, AAS, and water, along with the respective mixing durations and mixer speeds. The differences in procedures between ZCC and ZCC mortar highlight the influence of material composition and mixing techniques on the final properties of the mixtures.

The study’s findings demonstrated that the most favorable outcomes, in terms of compressive strength, setting time, and workability, were achieved using mixing procedures 4 and 8 for Class C FA mortars and Class F FA-based ZCCs, respectively. A critical observation was that pre-mixing the dry components before introducing the alkaline activator significantly improved the homogeneity and overall performance of the final mixture. Furthermore, increasing the mixer speed from 136 revolutions per minute (rpm) to 281 rpm and extending the mixing time of the alkaline activator solution from 1 minute to 5 minutes—prior to its gradual incorporation into the dry mix—further enhanced the setting characteristics, mechanical properties, and workability of ZCC.

CURING CONDITIONS

Curing plays a vital role in the development of mechanical and durability properties in Zero-Cement Concrete (ZCC), particularly influencing its fresh and hardened behavior, resistance to chemical attack, and long-term performance. The curing regime—comprising both the type and duration—interacts with numerous factors such as the chemical composition of precursor materials, activator type and molarity, ambient temperature, and the extent of calcium silicate hydrate (C–S–H) formation [38]. Experimental findings have consistently shown that an extended curing period significantly enhances the compressive strength of ZCC. Increases in curing time from 7 to 28 days, and further to 90 days, are generally associated with progressive strength development. This behavior closely mirrors that of OPC concrete. Particularly beyond 90 days, the formation of calcium-rich gel phases contributes to a notable increase in strength at later ages [39].

Table 2. Mixing procedures reported in the literature for ZCC and ZCC Mortar

Precursor Type	Step 1 Components	Mixing Time (min)	Step 2 Components	Mixing Time (min)	Step 3 Components	Mixing Time (min) or until homogeneous
FA Class F FA Class C GGBFS FA + GGBFS	CA, Sand, FA and/or slag	1–3	SS and SH	1–5	Water and SP (if needed)	5
FA Class F	FA and SH	5	Aggregate	5	SS	5
FA Class F, FA Class C	FA and SH	0.5–5	SS	1	Aggregate	1–3
FA Class F FA Class C	All dry ingredients	2–4 or until consistent	SS and SH, Water, SP (if needed)	2–8	–	–
FA + Additives (e.g., nano-silica, nano-alumina, rice husk)	All dry ingredients	1 or until consistent	SH	Until consistent	SS	5
FA Class C	All dry ingredients	1 or until consistent	SS	2	SH (solid form)	10
FA Class F	FA and aggregate	3	Fluid phase (SH and SS)	4	–	–
FA + GGBFS	CA, Sand	3	FA and GGBFS	3	SH, SS, SP (if any)	4
FA Class F	Solid constituents	3	Liquid constituents	3	SP	4
FA Class F	FA with Aggregates	2	Alkaline liquid, Water, SP	3–5	–	–

Table 3. Mixing procedures for ZCC and ZCC mortar [39]
A. ZCC (Class C FA-based)

Trial	Step 1	Time	Step 2	Time	Step 3	Time	Step 4	Time	Step 5	Time	Step 6	Time	Final Mix Time
1	CA + Sand	1	FA	1	AAS	1	Wt	1	–	–	–	–	3
2	FA	–	Wt	–	AAS	1	–	–	–	–	–	–	3
3	FA	–	W	–	SH	2	–	–	SS	1	–	–	3
4	FA	–	¼ W	–	AAS	1	–	–	¾ W	1	–	–	3
5	FA	–	½ W	–	½ AAS	1	–	2	½ Wt	1	½ AAS	1	3

6	½ W	–	FA	–	½ Wt	1	–	–	½ AAS	1	½ AAS	1	3
7	FA	–	Wt	–	½ AAS	1	–	1	½ AAS	1	–	–	3
8	FA	–	Wt	–	AAS	5	–	–	–	–	–	–	5

B. ZCC mortar (Class C FA-Based)

Trial	Step 1 Components	Time (min)	Step 2 Components	Time (min)	Step 3 Components	Time (min)	Mixer Speed (rpm)	Final Mix Time (min)
1	FA + Sand	1	AAS	1	Water	1	136	2
2	–	–	Wt	–	AAS	1	136	4
3	–	–	Wt	–	AAS	1	281	4
4	–	–	Wt	–	AAS	5	281	5

Gomaa et al. [39] investigated the effects of different curing regimes on ZCC performance. The first regime involved high-temperature curing in an electric oven at 70 °C for 24 hours. The second adopted ambient curing at 23 ± 2 °C for 7 days. Following demoulding, specimens were subjected to two post-curing storage methods in accordance with ASTM C39-2016: (1) exposure to laboratory air at room temperature, and (2) sealing in plastic bags to prevent moisture loss. These methods were found to significantly affect the hydration and performance of the final concrete.

Similarly, Hongen et al. [40] explored curing strategies for low-calcium FA-based geopolymer concrete (GPC), utilizing either dry oven curing (24 hours at 60 °C) or steam curing, in addition to ambient curing without external heat. Their findings indicate that the selection of curing method should be aligned with the type of fly ash used. Specifically, high-temperature curing is more suitable for FA Class F, whereas ambient or moisture curing is more appropriate for Class C FA-based ZCCs [37]. Interestingly, dry oven curing produced higher compressive strengths compared to steam curing in several cases.

For FA-based concretes, moisture curing is typically performed using either tap water or lime-saturated water. The use of hydrated lime [$Ca(OH)_2$] ensures a stable calcium ion concentration in solution (about 2 grams per liter or 0.9 pounds per 55 gallons), which helps mitigate the leaching of calcium carbonate ($CaCO_3$) from the concrete matrix [41]. This approach aligns with ASTM C511-2013 guidelines [42].

A variety of curing techniques have been employed in previous studies, including oven curing with or without steam, ambient curing at room temperature, and moist curing using water or lime-saturated water. Based on current research, the following recommendations have been proposed for effective curing of FA-based ZCC: After casting, specimens should rest for at least two hours at room temperature (23 ± 2 °C) before curing begins. Although curing durations of 6–8 hours may suffice in some cases, longer curing periods—up to 48 hours or more—generally yield superior strength and durability. At lower ambient temperatures (below 21–23 °C), FA-based ZCC mixtures may require extended curing times (more than 24 hours) to complete setting due to slower reaction kinetics. While difficult to implement in field conditions, oven curing at elevated temperatures (600–900 °C) has been shown to accelerate polymerization and improve gel structure formation, resulting in increased compressive strength and durability. For both oven and ambient curing, specimens should be wrapped in plastic sheets after demoulding to prevent moisture evaporation, which is critical for ongoing polymerization. Finally, maintaining specimens at room temperature for longer durations can be beneficial for enhancing strength development, especially in Class C FA-based mixes.

MECHANICAL CHARACTERISTICS OF FLY ASH-BASED ZERO-CEMENT CONCRETE

The compressive strength (f'c) is a primary indicator of the quality and performance of Zero-Cement Concrete (ZCC). Several parameters influence the strength development of ZCC, especially those based on fly ash (FA), including but not limited to the molarity of sodium hydroxide, the ratio of sodium silicate (SS) to sodium hydroxide (SH), the silica modulus (SiO_2/Na_2O) of the SS solution, binder type, the ratio of alkaline activator solution (AAS) to binder, water-to-binder ratio, binder-to-aggregate ratio, mix proportions, mixing procedure, initial resting time, curing conditions, and the proportion of superplasticizer relative to the binder [43].

It has been reported that compressive strength increases when the AAS-to-solid mass ratio decreases—similar to how a lower water-to-cement ratio enhances strength in conventional concrete [36]. The AAS comprises the water content in both SH and SS, while the "solid mass" includes FA and the solid content of SH and SS. Furthermore, other influential factors positively contributing to compressive strength include curing temperatures ranging between 30 °C and 90 °C, increased molarity of SH (up to 10M–14M), a higher SS/SH ratio (up to 2.5), and extended curing durations [43].

In addition to compressive strength, other mechanical parameters such as modulus of elasticity (MOE), tensile strength (f't), and modulus of rupture (f'r) have also been extensively studied. These properties are similarly affected by the factors influencing compressive strength. Numerous researchers have analyzed the stress–strain behavior of FA–ZCC to estimate MOE [49]. While the MOE of conventional concrete is typically governed by the properties of aggregates and the paste matrix (as described by ACI 318), studies show that the MOE of FA–ZCC is either slightly lower or comparable [44] to that of OPC-based normal concrete.

The MOE of FA–ZCC has been described using various empirical equations. Singh et al. [33] reported MOE values ranging from 20 to 40 GPa for FA–ZCC, while for traditional normal concrete (NC), the typical range is 25 to 35 GPa. These variations in MOE across studies are primarily attributed to differences in fly ash type (Class F vs. Class C), mix proportions, dosage levels, and mixing procedures. Furthermore, the tensile strength of FA–ZCC produced using SS–SH as activators has been found to align closely with the predictive expressions outlined in ACI 318 and, in some cases, to exceed the values suggested by Eurocode 2 [45].

Compressive strength values for geopolymer concrete (GPC) vary widely based on mix composition and curing regime, typically ranging between 38.2 MPa and 55.63 MPa [46], [47], [48]. Flexural strength results are also promising, with performance comparable to that of OPC concrete, indicating the feasibility of FA–ZCC in structural applications [49].

CONCLUSION AND FUTURE RESEARCH NEED

The increasing global demand for sustainable construction materials has intensified the search for alternatives to Ordinary Portland Cement (OPC), primarily due to its substantial contribution to global CO_2 emissions and environmental degradation. Zero-Cement Concrete (ZCC), particularly that based on fly ash (FA), has emerged as a promising and environmentally responsible solution. This review comprehensively explored the components, mix design strategies, mixing techniques, curing conditions, and mechanical properties of FA–ZCC.

Fly ash, as a by-product of coal combustion, demonstrates excellent potential as a primary precursor in alkali-activated binder systems. Combined with suitable alkaline activators such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), FA–ZCC exhibits mechanical properties—especially compressive strength, modulus of elasticity, and flexural performance—that are comparable to or exceed those of conventional OPC-based concrete. Numerous parameters including molarity, activator ratios, binder-to-aggregate proportions, curing regime, and mixing procedure significantly influence the final performance of FA–ZCC. However, the lack of standardized mix design procedures and universally accepted curing and processing guidelines continues to limit the widespread adoption of ZCC technologies.

Despite the substantial progress observed in laboratory-scale studies, several challenges and research gaps remain. One of the key challenges is the standardization of mix design, with an urgent need to develop universally applicable guidelines for proportioning FA–ZCC mixtures. These guidelines should account for variations in precursor composition, activator chemistry, and target performance. Additionally, while short-term mechanical properties are promising, long-term durability studies are crucial. There is a need for comprehensive investigations on the durability of FA-based ZCC under diverse environmental conditions, such as sulfate attack, freeze–thaw cycles, and carbonation. Another area that requires attention is the exploration of in-situ curing strategies. Field-curing approaches that are compatible with construction site constraints must be developed, especially alternatives to high-temperature oven curing, which may not be feasible for large-scale or in-situ applications. Furthermore, to support large-scale implementation, future research should include life cycle analysis (LCA), embodied energy evaluation, and cost–benefit comparisons between FA–ZCC and traditional concrete systems. The utilization of local waste materials is another important aspect; further studies should explore the incorporation of regionally available industrial by-products or natural pozzolans as supplementary or alternative binders to fly ash. Finally, research efforts should shift toward validating the performance of ZCC at the structural element and system level to demonstrate its practical viability in applications such as bridges, pavements, and high-rise construction.

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