Embedding Aluminum in Cementitious Systems: Risks, Mitigation, And Future Perspectives

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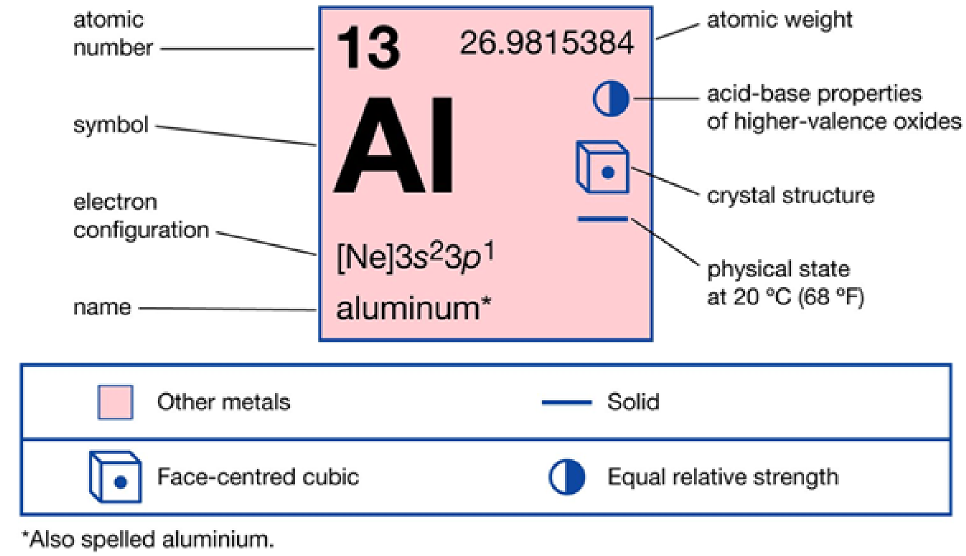
Introduction

Aluminum, a non-ferrous metal characterized by low density and strong corrosion resistance, is extensively utilized across many industrial sectors (Polmear et al., 2017). In building materials, it offers key advantages such as light weight and formability (**Figure 1**), making it suitable for elements like window frames, panels, and exterior façades. Nevertheless, the metal's strong chemical reactivity in alkaline media poses significant challenges for maintaining long-term stability within cement-based composites. Upon exposure to air, aluminum instantly develops a compact and protective oxide layer that stabilizes the surface in neutral or slightly acidic media. In the highly alkaline pore solution typical of ordinary Portland cement (OPC), however, this film gradually deteriorates. As a consequence, electrochemical activity accelerates the dissolution of aluminum, accompanied by hydrogen generation and the accumulation of expansive hydroxide or oxide phases. Such processes not only degrade the metal but also damage the integrity of the adjacent cementitious matrix through cracking, blistering, and detachment.

Therefore, a critical engineering question arises: *Can aluminum be safely embedded in concrete, and if so, under what controlled conditions?*

Figure 1

Properties of the Element Aluminum



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Explanatory note. The figure presents the fundamental physical and mechanical properties of aluminum relevant to its application in cementitious systems.

There remains considerable debate regarding the interaction of aluminum, whose role in transportation, aviation, and architectural applications is well established, with cementitious system materials. In OPC systems, the highly alkaline pore solution (pH ≈ 12–13.5) destabilizes the protective oxide film, leading to rapid dissolution, hydrogen evolution, and the accumulation of expansive corrosion products. These phenomena collectively threaten both the durability of aluminum components and the structural integrity of concrete.

International standards such as Eurocode 9 (CEN, 2009), ACI (2018), and the Concrete Institute (2025) restrict the direct embedding of untreated aluminum in concrete. Nonetheless, recent studies have focused on mitigation strategies and novel applications (Abdalla et. al., 2020; Runningen et. al., 2021; Elsamak et. al., 2025). These include the incorporation of supplementary cementitious materials (SCMs) to lower pore solution alkalinity, the use of alternative binders such as magnesium potassium phosphate cement (MKPC) with reduced pH, and the application of advanced protective coatings to prevent direct contact between aluminum and the cement matrix. Moreover, aluminum has been investigated as a structural component in concrete-filled aluminum tube (CFAT/ATCC) systems and as a recycled additive to enhance mechanical, thermal, and multifunctional properties of cementitious composites. These emerging approaches align with sustainable construction principles by reducing carbon emissions and promoting circular material use.

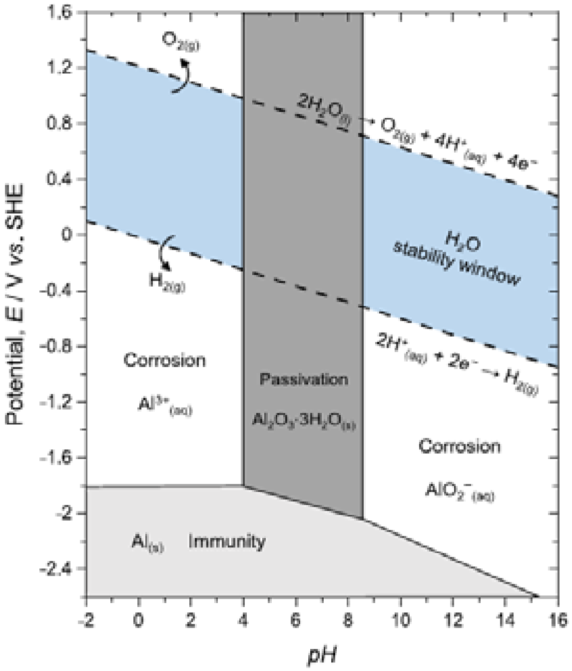
The objective of this chapter is to systematically evaluate the electrochemical behavior of aluminum in cementitious environments, to summarize the requirements of international standards, and to highlight advances in mitigation and emerging applications. Particular emphasis is placed on corrosion mechanisms, galvanic interactions with steel reinforcement, and the potential contribution of aluminum waste to sustainable construction. By identifying research gaps and future perspectives, this chapter aims to provide a comprehensive framework for assessing the safe and effective integration of aluminum into modern concrete technologies.

Electrochemical Behaviour of Aluminum

The electrochemical response of aluminum varies considerably depending on the composition of the surrounding electrolyte. Under highly alkaline conditions, hydroxide ions disrupt the protective oxide barrier, reflecting the strong interaction between aluminum and water molecules. Consequently, the metal acquires a markedly negative potential and experiences rapid dissolution, accompanied by hydrogen generation and the production of aluminate species. In aluminum alloys reinforced with ceramic particles, the electrochemical behavior may also differ due to altered surface characteristics and microstructural uniformity (Uygur et al., 2004; Uygur, 2024). Under these conditions, aluminum can also undergo anodic dissolution at high current densities without significant polarization (Hernández et. al., 2011), as illustrated in the Pourbaix diagram summarizing aluminum in aqueous environments (**Figure 2**).

Figure 2

Pourbaix Diagram of Aluminum in Aqueous Solution (Leung et. al. 2021)



Explanatory note. The diagram illustrates the electrochemical stability of aluminum species as a function of pH and potential, highlighting the instability of aluminum in highly alkaline media.

When aluminum comes into contact with steel reinforcement in concrete, a galvanic cell is established due to the potential difference between the two metals. Aluminum acts as the anode and undergoes dissolution, while steel behaves as the cathode, accelerating localized corrosion. As a result, hydrogen gas evolution and severe pitting corrosion occur at the interface of aluminum and steel in the presence of chloride ions. Studies on discontinuously reinforced aluminum matrix composites demonstrated that fatigue life and crack propagation are strongly influenced by particle size and distribution.

Concrete and GFRC (Glass Fiber Reinforced Concrete), as cementitious system materials, typically create highly alkaline environments with a pH range of 11–13. According to the Pourbaix diagram, at these high pH levels and depending on the electrochemical potential, aluminum tends to corrode by dissolving into AlO_2^- ions. Notably, at pH values above 9, the protective passive layer on aluminum deteriorates, losing its effectiveness. Therefore, direct contact between aluminum and such alkaline environments poses a risk to the material's structural integrity.

$$2Al + 6H_2O + 2OH^- \rightarrow 2[Al(OH)_4]^- + 3H_2\uparrow \quad (1)$$

Bare (uncoated) aluminum should not be embedded directly in fresh concrete. The highly alkaline pore solution (pH ~12–13.5) attacks aluminum, forming aluminum hydroxide and releasing hydrogen gas. This reaction can produce voids, loss of bond, surface blistering, and long-term corrosion of the aluminum element. Supplementary cementitious materials (SCMs) such as fly ash and silica fume have been shown to reduce pore solution alkalinity, thereby slowing down aluminum corrosion. Runningen et al. (2021) reported that aluminum alloys embedded in cement pastes with a high SCM content exhibited greater chemical stability and reduced hydrogen gas evolution than plain OPC systems.

International standards are quite clear regarding the usability of aluminum in concrete, and they stipulate that aluminum can be used in concrete for various applications, including construction, infrastructure, and engineering projects. The American Concrete Institute (ACI; 2018) has stated in its documentation that direct contact between untreated aluminum and fresh concrete results in the release of copious amounts of hydrogen gas and the formation of surface defects. Consequently, the embedding of aluminum without a protective coating is strictly prohibited. Similarly, Eurocode 9 (CEN 1999-1-1:2009, Annex D.3.4) stipulates that aluminum must be coated with at least two layers of heavy-duty bituminous paint or hot bitumen when embedded in concrete and that the coating must extend at least 75 mm above the concrete surface. It also requires the use of plasticised coal tar in chlorinated concrete and strictly prohibits direct electrical contact between steel and aluminum. The Concrete Society's current guide also reports that aluminum undergoes severe initial attack in environments containing calcium hydroxide; that the risk of cracking and spalling increases due to hydrogen gas formation; that this effect is exacerbated when calcium chloride additives are used; and that prestressed concrete systems carry a risk of hydrogen embrittlement. These standards show that there is a general agreement: aluminum cannot be safely put into concrete without strong ways to protect it. The focus on coatings, electrical insulation, and design-specific measures is a result of the understanding that aluminum's natural instability in alkaline pore solutions can lead to risks that affect the whole structure.

A comparative assessment of international standards reveals converging principles. Although developed within different regulatory contexts, ACI, Eurocode 9, and the Concrete Society guidelines align on several critical points, particularly regarding coating requirements, chloride restrictions, and the necessity of isolating aluminum from steel.

- **ACI (2018):** It is stated that untreated aluminum should not come into direct contact with fresh concrete; otherwise, intense hydrogen gas release and surface defects will occur. Therefore, embedding operations must be carried out using appropriate protective coatings.
- **Eurocode 9 (CEN, 2009):** When aluminum is embedded in concrete, it must be coated with at least two layers of bituminous paint or hot bitumen. The coating must extend at least 75 mm above the concrete surface. Additionally, direct electrical contact with steel is strictly prohibited, and the use of plasticised coal tar is recommended for chlorinated concrete.
- **Concrete Society (2025):** It emphasises that aluminum undergoes severe corrosion in environments containing calcium hydroxide and, in particular, calcium chloride; that the risk of cracking and spalling increases due to hydrogen release; and that special attention must be paid to the risk of hydrogen embrittlement in prestressed concrete.

A study by Herting and Odnevall (2021) investigated the long-term corrosion behavior of aluminum (Al) and zinc (Zn) embedded in concrete under anaerobic conditions, simulating the Swedish repository environment for low- and intermediate-level radioactive waste. The samples were immersed in artificial groundwater (AGW) for up to two years. Aluminum exhibited high initial corrosion rates, which gradually decreased and stabilized over time. After 104 weeks, some Al-containing concrete cylinders developed cracks, attributed to hydrogen gas evolution and expansion of corrosion products. Zinc samples, in contrast, showed lower corrosion rates and maintained the structural integrity of the concrete. The study concluded that AGW exposure tests can reliably predict long-term corrosion performance of metals embedded in concrete under similar conditions.

Figure 3

Representative concrete cylinder after two years, excluding two aluminum-containing samples.

(a) (b)

Figure 3. (a) Concrete cylinder representative for all samples and time periods except two Al containing cylinders (out of five) exposed for two years and (b) Concrete cylinder containing Al that cracked after two years of exposure.

Explanatory note. Cracking observed in aluminum-containing samples results from internal hydrogen gas evolution and volumetric expansion of corrosion products.

After two years of exposure, 40% of the Al-containing concrete cylinders developed visible structural cracks (up to 3 mm wide), compromising the integrity of the concrete matrix. These cracks originated from internal stresses due to the corrosion process, as shown in **Figure 3b**, while no such degradation was observed in zinc-containing samples (**Figure 3a**). This confirms that aluminum poses a greater risk to concrete durability under repository conditions, whereas zinc exhibits more stable long-term behaviour.

Alternative Binding Systems and Corrosion Behavior

Traditional Portland cement (OPC) has high alkalinity (pH 12.5–13.5), and in this environment, aluminum rapidly reacts with hydroxide ions to produce hydrogen gas. The formation of large-volume hydrated oxide products (e.g., bayerite, gibbsite) on the aluminum surface and the initiation of cracks in the concrete matrix are caused by this process (Korec et. al., 2023; Abi Aad et. al., 2017). In recent years, studies have been conducted on alternative binding systems to address this problem. Notably, magnesium potassium phosphate cement (MKPC) engenders a distinctly more propitious chemical milieu for aluminum by virtue of its lower pH values (4–9). Perona et al. (2023) investigated A1050 and AA5754 aluminum alloys in both OPC and MKPC systems. They reported that, after 15 days, 11.6–17.8 L/m^2 of hydrogen gas was released in the OPC system. In the MKPC system, however, this value was only 0.14–0.33 L/m^2. These results suggest that MKPC can reduce aluminum corrosion by at least one order of magnitude. Additionally, evaluations by Fernández-García and Alonso (2025) indicate that while low corrosion current and H2 volume were observed in the MKPC environment during the initial stages, long-term alkalization may weaken this protective effect. These findings suggest that MKPC could be a more suitable alternative to conventional binders for aluminum, particularly for immobilising nuclear waste and for use in concrete applications requiring special durability.

As shown in **Figure 4a**, corrosion of aluminum in the high-pH concrete environment led to the formation of visible voids above the embedded metal, caused by rapid hydrogen gas evolution during the early stages of exposure. This gas generation weakened the adhesion between the aluminum and the surrounding concrete. **Figure 4b** illustrates a gas vent channel extending from the void to the outer surface of the concrete cylinder, providing a pathway for gas escape. These features indicate that the corrosion of aluminum not only affects the metal but also alters the structural continuity of the concrete matrix.

Figure 4

Voids formed at the top end of the aluminum sample embedded in concrete, and the gas vent extending from these voids to the outer surface of the concrete cylinder is shown.

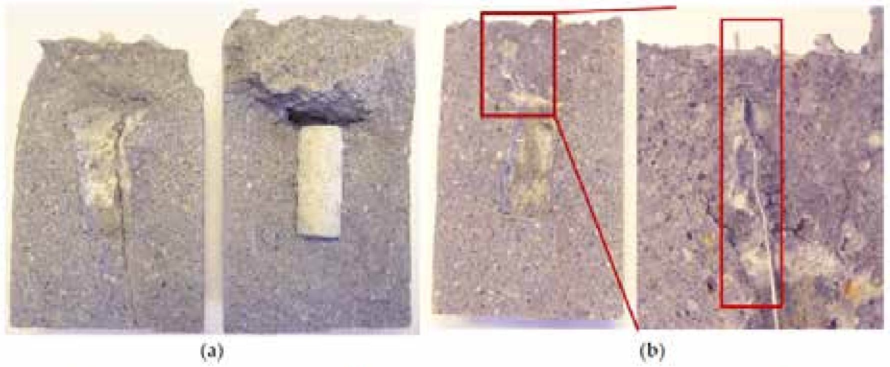


Figure 4. (a) Voids formed at the top end of the Al sample embedded in concrete and (b) Gas vent leading from the top of the void to the outer upper surface of the concrete cylinder.

Explanatory note. Gas vent channels originating from hydrogen evolution are visible, illustrating the effect of aluminum corrosion on the surrounding concrete matrix.

Calderón et al. (2022) investigated the corrosion behavior of aluminum embedded in cementitious environments with high alkalinity (pH > 12). The study involved immersing aluminum samples in a synthetic pore solution and analyzing the resulting corrosion products using SEM, EDX, and XRD. The findings revealed the formation of hydrated aluminum oxide phases, which expand and generate internal stresses in the cement matrix. These stresses are capable of initiating cracks, potentially compromising the structural integrity of the system. The results contribute valuable insights into the long-term electrochemical stability of aluminum in concrete and similar materials.

Figure 5 presents a scanning electron microscopy (SEM) image of an aluminum sample surface after two weeks of exposure to a high-pH synthetic pore solution (pH ≈ 13.5). The image reveals the formation of dense and irregular corrosion products covering the surface. These products are primarily hydrated aluminum oxides, such as bayerite and gibbsite. The morphology indicates significant volume expansion, leading to surface roughness and localized delamination. This supports the conclusion that aluminum corrosion in alkaline environments can generate internal stresses, contributing to cracking and potential degradation of the surrounding cementitious matrix.

Figure 5

EM images of Al plates embedded in Portland cement pastes hydrated for three days.

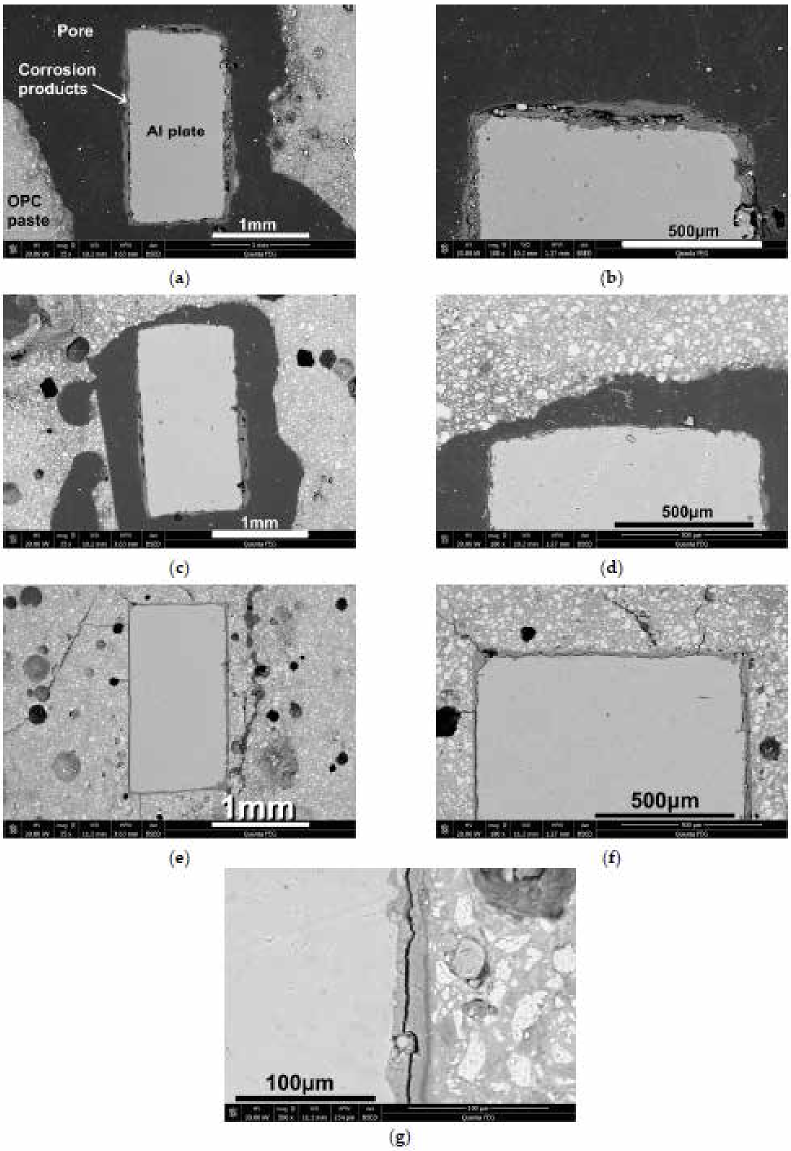


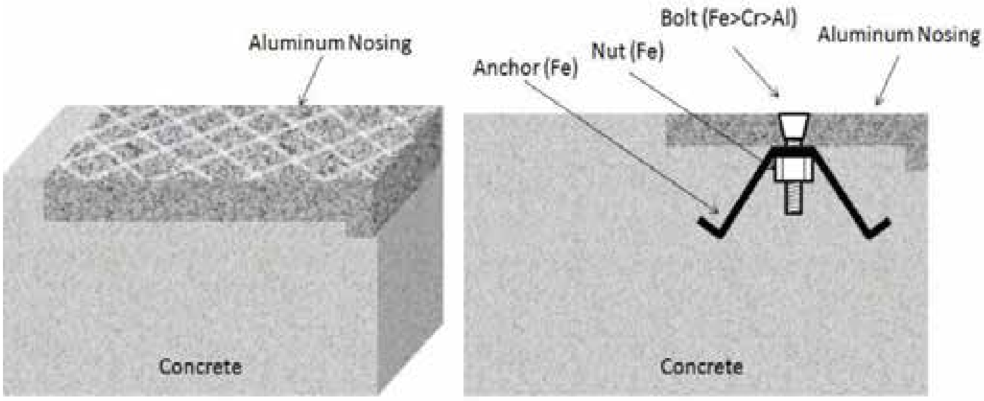
Figure 5. SEM BSE images of Al plates in hardened OPC pastes with various amounts of PAS hydrated at 3 days: (**a**) and (**b**): PC-P0; (**c**) and (**d**): PC-P3; and (**e**–**g**): PC-P6 samples.

Explanatory note. Dense and irregular hydrated aluminum oxide layers indicate volume expansion and local delamination on the metal surface.

Jana and Tepke (2009) investigated the corrosion of aluminum nosings fixed with steel fasteners on outdoor concrete stairs (**Figure 6**). Galvanic corrosion occurred where aluminum came into contact with steel, particularly in the presence of chloride ions. This resulted in significant metal loss, the nosings detaching, and the surrounding concrete cracking or spalling. The corrosion products consisted of hydrated aluminum hydroxide crystals (gibbsite, bayerite, and boehmite) and silicon-rich banded microstructures. The expansion of these products caused mechanical stress and material failure.

Figure 6

Schematic illustration showing the fixation of the aluminum nosing to concrete using a steel anchor, nut, and bolt.



Explanatory note. The figure depicts galvanic contact between aluminum and steel, which accelerates localized corrosion in the presence of chlorides.

Figure 7 shows the results of field observations of the deterioration of concrete stairs with aluminum nosings. This deterioration is primarily caused by aluminum interacting with the concrete environment's high alkalinity, moisture, and chloride ions. The resulting volumetric expansion causes the nosings to separate from the concrete surface (debonding), resulting in cracking of the concrete. Galvanic corrosion develops in areas that are in contact with steel anchors. The direct contact between aluminum and steel within the concrete accelerates corrosion in the presence of chlorides, leading to significant thickness loss of the metal beneath the nosings.

Figure 7

Field-observed deteriorations in concrete stairs with aluminum nosings.

Explanatory note. Cracking and debonding occur due to aluminum's reaction with alkaline concrete and galvanic coupling with embedded steel components.

In cases of galvanic corrosion where aluminum is coupled with steel, hydroxyl ions play a key role in the dissolution of aluminum. These ions originate not only from the concrete matrix but also from the cathodic corrosion reactions occurring at the steel surface. This dual source of hydroxyl ions significantly accelerates the corrosion of aluminum compared to scenarios without steel or without electrical coupling to steel.

Galvanic interactions between aluminum and steel result in the preferential dissolution of the more anodic aluminum, while the more cathodic steel remains preserved. Chloride ions further exacerbate this process by acting as catalysts, sustaining both the galvanic current and the aluminum corrosion. This mechanism is analogous to the use of sacrificial zinc or aluminum anodes in cathodic protection systems, where these reactive metals are intentionally corroded to protect embedded steel and extend its service life. In such systems, aluminum functions as the anode, releasing electrons that travel through the metallic pathway to the steel cathode. Meanwhile, hydroxyl ions migrate through the pore solution in the concrete toward the aluminum surface, where they react to form aluminum hydroxide.

Feldman, Clifton, and Morgan (1983) provided one of the earliest systematic investigations of aluminum behaviour in alkaline cement mortars, demonstrating that corrosion intensifies sharply above pH 13, whereas relative passivity can be sustained below pH

12.4. Experiments on various types of cement revealed that dissolution accelerated when the formation of a protective film was prevented. The authors recommend formulations supported by low pH systems or passivating additives for aluminum use in concrete. These findings suggest that the use of aluminum in concrete should be carefully considered. Comparative studies indicate that aluminum alloys such as 6061-T6 display superior resistance to atmospheric and chloride-induced corrosion compared to carbon steel; however, in highly alkaline environments dominated by $Ca(OH)_2$, aluminum shows poor durability. Luo, Li, and Xing (2022) concluded that while steel deteriorates rapidly under chloride attack, aluminum suffers severe instability in cement pore solutions, highlighting the distinct but complementary corrosion vulnerabilities of both materials. While galvanic corrosion limits direct embedding, structural innovations have opened new routes for integrating aluminum safely into composite systems.

Galvanic Corrosion and Aluminum–Steel Interaction

Apart from the corrosion of aluminum in concrete, there is a risk of galvanic corrosion, especially when it comes into direct contact with steel reinforcement or anchorage elements, which increases the risk of galvanic corrosion. In galvanic couples, aluminum is more anodic and dissolves rapidly, while steel remains protected[21]. Recent electrochemical tests in simulated pore solutions confirm this, showing that aluminum–steel couples develop significant potential differences, which lead to accelerated aluminum dissolution (Fabris et. al., 2024; Ikeuba et. al., 2024).

Galvanic corrosion is also exacerbated by the ionic conductivity of the concrete pore fluid. Hydroxide ions (OH^-), produced at cathodic sites, migrate and accelerate aluminum dissolution (Kinoshita et. al. 2013). In the presence of chlorides, thickness losses occur at an accelerated rate. Historical investigations further confirm that aluminum embedded in chloride-containing concrete undergoes significant galvanic corrosion due to moisture-mediated current paths (Pitts, 1958). To prevent these interactions, international guidelines (ISO 2022; Yao et. al., 2025) emphasize avoiding direct electrical contact between aluminum and steel by using dielectric sleeves or insulation layers. These field and laboratory findings clearly demonstrate that unprotected aluminum in concrete poses serious risks. Based on standards and recent field (Elsamak et. al., 2024; Taheri-Shakib et. al., 2024), the following checklist outlines key safety requirements for practical applications:

i. Coating requirement: Aluminum surfaces must be coated with at least two coats of bituminous paint or equivalent epoxy (Yao et. al., 2025); in early empirical reports, a bituminous coating effectively suppressed corrosion for extended periods (Zheng et. al., 2019).

ii. Coating overlap: The protective coating must overlap the concrete surface by at least 75 mm (Yao et. al., 2025).

iii. Avoidance of chloride additives: $CaCl_2$ or similar chloride additives should not be used; such additives exacerbate aluminum corrosion (Wright& Jenks 1963).

iv. Preventing direct contact with steel: A dielectric sleeve, plastic separator, or insulating mastic layer must be present between aluminum and steel (Engineering Express 2025).

v. Control of initial contact with fresh concrete: Unprocessed aluminum should not be embedded in fresh concrete, as this can result in intense hydrogen release and surface defects (Geng et. al., 2025; Runningen et. al., 2021).

vi. Evaluation of alternative binders: In special applications, binders with lower pH, such as MKPC, may be preferred (Poras et. al., 2023).

vii. Drainage and ventilation: Drainage and gas venting pathways should be provided around embedded aluminum parts to prevent hydrogen gas accumulation (Safyari et. al., 2023).

viii. Regular inspection: Surface cracks, blisters, and gas vent marks in structures where aluminum is embedded should be checked periodically (Xiao et. al., 2015).

xi. Selection of low pH systems: The use of high silica fume (up to 50%) in OPC-based mixtures reduces the pore solution pH to approximately 10.5, significantly reducing aluminum corrosion and hydrogen release (Fernández-García, 2024).

Guidance will be provided on this control list during both field applications and the design phase to ensure the safe use of aluminum in concrete.

Beyond corrosion-related concerns, recent research has also explored novel applications of aluminum in concrete. These include its role in structural composites such as concrete-filled aluminum tubes (CFAT/ATCC) and the reuse of aluminum waste as a cementitious additive. The following sections provide a detailed discussion of these applications, highlighting both their potential benefits and current limitations. For example, Liu, Wang, and Gao (2025) examined the bonding behaviour and bond-slip mechanism of concrete-filled aluminum alloy tubes (CFAT), demonstrating superior bond strength in circular sections compared to square ones and emphasising the material's advantages, such as being lightweight and recyclable, in sustainable structural design. Similarly, Al-Darraji et al. (2025) studied CFAT pile groups under combined vertical and lateral loads, demonstrating the influence of the slenderness ratio on both vertical and lateral capacity, a key consideration in foundational applications.

In terms of material reuse, research into using aluminum waste in cementitious systems is promising. Xu et al. (2023) examined the addition of secondary aluminum ash to reactive powder concrete and found improvements in Aslan (2023) tested the use of industrial metallic waste chips, including aluminum, in reinforced concrete beams and reported significant increases in flexural strength and ductility at low replacement rates.

When aluminum is coupled with steel reinforcement, galvanic corrosion accelerates aluminum dissolution. Aluminum acts as the anodic metal, while steel is cathodic. Chloride ions exacerbate this reaction, leading to rapid metal loss and concrete cracking. International codes mandate dielectric barriers between aluminum and steel to prevent such interactions.

Alternative Structural Applications: Concrete-Filled Aluminum Tubes.

Recent research has expanded the potential structural applications of aluminum in concrete systems. For example, Liu, Wang, and Gao (2025) investigated the bond-slip behaviour of concrete-filled aluminum alloy tube (CFAT) columns. They found that circular CFAT specimens exhibited significantly higher bond strength (0.77–1.77 MPa) than square ones (0.22–0.51 MPa). They also proposed a constitutive bond-slip model to predict performance. Zhao et al. (2022) studied ATCC (with circular hollow sections) under axial compression. They demonstrated that, while circular hollow aluminum enclosures provide enhanced confinement and strength potential, they are also susceptible to localised buckling depending on the thickness-to-diameter ratio.

While these findings highlight the critical influence of geometry and tube configuration on confinement effectiveness, they also reveal that aluminum's lower elastic modulus can lead to premature buckling, limiting its comparative strength against traditional steel tubes. Furthermore, current design codes, such as Eurocode 9, still lack explicit guidelines for CFAT or ATCC systems, indicating a clear need for standardisation and codification.

Use of Aluminum Waste as a Concrete Additive

In addition to structural components, aluminum waste materials have attracted attention as a partial replacement for cementitious materials. Pérez et al. (2022) investigated the incorporation of secondary aluminum chips into concrete mixes and found that low replacement levels (0.5–1.5% by weight of cement) increased tensile and flexural strength. However, higher additions (>3%) reduced workability and compressive strength, primarily due to increased porosity and gas release.

Recent studies have extended these findings. Elseknidy et al. (2020) demonstrated that incorporating aluminum dross (10% by cement mass) combined with fly ash and quarry dust enhanced both the compressive and flexural strengths of concrete mixes while maintaining workability. Conversely, Agor et al. (2023) examined the use of a blend of aluminum waste and sisal fibre in concrete. Results showed optimised flexural and compressive performance, particularly at low aluminum waste content (0.1%), which highlights the importance of precise dosage. Finally, Fathi et al. (2025) examined the use of aluminum chips and aluminum powder to create conductive concrete. Certain mixtures achieved improved mechanical strength and exhibited low electrical resistivity, opening up the possibility of using concrete for multifunctional 'heating' or de-icing applications. Overall, these findings suggest that recycled aluminum can significantly enhance the mechanical and functional properties of concrete, but only when the content and combination are optimised. It is essential to balance performance gains with durability and workability.

The evaluation of aluminum embedded in concrete environments reveals a complex interplay between material chemistry, electrochemical stability, and structural performance. Across the literature, a consistent finding is that the highly alkaline pore solution of ordinary Portland cement (OPC) (pH 12–13.5) rapidly destabilises aluminum's passive oxide layer, leading to severe corrosion, hydrogen gas evolution, and expansive corrosion products such as bayerite and gibbsite. These reactions not only degrade aluminum but also compromise concrete integrity by initiating cracks, voids, and loss of bond. Long-term studies, such as those of Herting and Odnevall (2021)[8], confirm that aluminum-containing concrete specimens develop visible cracks after prolonged exposure, while zinc samples remain largely intact, underlining aluminum's instability in conventional cementitious systems.

Conclusions and Future Perspectives

The interaction between aluminum and concrete is governed by both chemical and structural factors. In ordinary Portland cement (OPC), the highly alkaline pore solution (pH 12–13.5) destabilises the protective oxide layer on aluminum, leading to hydrogen gas evolution, dissolution, and the formation of expansive corrosion products such as bayerite and gibbsite. These reactions not only degrade the aluminum itself but also induce blistering, void formation, and cracking within the surrounding cement matrix. When aluminum is electrically connected to steel reinforcement, a galvanic cell forms, causing the aluminum to corrode faster—especially in environments containing chloride ions. International guidelines such as ACI, Eurocode 9, and the Concrete Society documents emphasize these risks and advise against embedding bare aluminum in uncured concrete. To ensure safety, they recommend applying protective coatings, maintaining electrical separation from steel, and avoiding chloride contamination during concrete preparation. These recommendations are based on consistent experimental findings showing that uncoated aluminum in OPC undergoes rapid corrosion, hydrogen release, and mechanical debonding.

Recent progress in materials science indicates that these corrosion issues can be alleviated through compositional modification. The incorporation of supplementary cementitious materials (SCMs) helps lower the alkalinity of the pore fluid and decelerates the electrochemical reaction rate. Likewise, using alternative binders, such as magnesium potassium phosphate cement (MKPC), creates a more stable and less corrosive medium, substantially limiting hydrogen release compared with ordinary Portland cement. Even with these improvements, protective surface treatments and electrical isolation from dissimilar metals remain crucial for durable performance. According to practical engineering guidance, applying proper coatings and galvanic isolation can effectively prevent dissimilar metal corrosion (URL-1). Supplementary cementitious materials (SCMs) such as fly ash, silica fume, and slag can reduce pore solution alkalinity, thereby slowing corrosion kinetics and hydrogen evolution. Alternative binders like magnesium potassium phosphate cement (MKPC) create a more benign chemical environment—lowering pH to the 8–9 range and reducing hydrogen evolution by more than an order of magnitude compared with OPC. Likewise, the application of bituminous, epoxy, or polymeric coatings, in combination with galvanic insulation, has been shown to provide effective long-term protection for aluminum components embedded in concrete.

Beyond corrosion mitigation, innovative structural and functional applications of aluminum in cementitious systems are gaining momentum. Concrete-filled aluminum tubes (CFAT/ATCC) exhibit favorable mechanical performance and recyclability when properly designed, although attention must be paid to local buckling effects due to aluminum's lower elastic modulus. Furthermore, the controlled incorporation of aluminum waste into concrete, at low dosages (<1–1.5% by weight of cement), has demonstrated improvements in flexural strength, shrinkage resistance, and multifunctionality such as electrical conductivity and de-icing potential. However, higher dosages can lead to excessive porosity and reduced compressive strength, underscoring the need for precise optimization. Taken together, the evidence presents a dual perspective. Untreated aluminum remains fundamentally incompatible with conventional OPC systems, a conclusion validated by international standards and decades of empirical data. Yet, under carefully engineered conditions, through binder modification, protective coatings, galvanic isolation, and controlled aluminum incorporation, it can be safely and effectively integrated into modern cementitious materials.

Future Perspectives: Further research should focus on developing hybrid low-alkali binders and multifunctional composite systems that permit the inclusion of aluminum without compromising structural stability. Special attention should be given to:

(i) tailoring pH-buffered cements with self-passivating additives,

(ii) designing advanced barrier coatings with self-healing or nanocomposite functionality,

(iii) employing surface treatments that improve aluminum–cement adhesion, and

(iv) expanding the recycling of industrial aluminum waste within circular economy frameworks.

(v) incorporating corrosion inhibitors into the cement matrix to mitigate aluminum corrosion.

Such advances will enable the transition toward sustainable, low-carbon, and multifunctional construction materials, where aluminum, once deemed incompatible, may serve as a lightweight, durable, and recyclable component in the next generation of eco-efficient infrastructure. Ultimately, by bridging materials science and structural engineering, the safe integration of aluminum into cementitious systems represents a key step toward sustainable infrastructure design.

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