

Alternative Cements: Recent Developments and Future Directions

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ABSTRACT

Concrete is the most utilized construction material and the second most consumed material on earth after water. As a consequence, its manufacture and use imparts global durability and environmental consequences. The manufacture of conventional ordinary Portland cement (OPC), the main constituent in concrete, for example, alone accounts for 5–8% of global CO₂ emissions worldwide. In addition, the main durability challenges of OPC are associated with the chemistry of its binder. In recent years, increased demand for sustainable building materials with lower CO₂ emissions and equivalent (or higher) service lifespans have prompted the development of alternative and novel cementitious materials to supplement and/or in some applications replace the use of OPC concrete in a variety of building and infrastructure engineering projects. Many of these alternative and novel cementitious material systems and approaches generally demonstrate lower CO₂ emissions during production (up to 50% CO₂ reductions) and increased durability when subjected to harsh conditions (e.g., lower shrinkage, higher acid resistance) when compared to OPC. This paper synthesizes and presents the general classification, characteristics, and current applications of four promising alternative cementitious material systems, namely (1) high-aluminate, (2) super-sulfated slag, (3) alkali-activated, and (4) carbonate-based cements (e.g., bio-cements). We will highlight the basics of alternative cement chemistries, their environmental impacts, and relevant material properties (i.e., fresh- and hardened-state properties) compared to OPC concrete. The discussions presented herein are supplemented with specific case-study examples of real-world applications and aim to serve as an inspiring platform for researchers, educators, and engineering professionals to conceptualize how next-generation cementitious materials can (and will) shape our built environment.

INTRODUCTION: LIMITATIONS OF OPC CONCRETE

The customary use of ordinary portland cement (OPC) concrete has resulted in its inappropriate application for unique infrastructure applications. For example, concrete slabs for rocket launch pads necessitate lining with refractory or heat-resistant materials (i.e., refractory bricks or fire suppressant coatings) because, when OPC concrete is subjected to high temperatures (i.e., fire), its deterioration may result in explosive spalling and reductions in compressive strength [1], [2]. Another example is the unprecedented and deleterious biogenic production of sulfuric acid within sewer infrastructure, which has resulted in reductions in the service life of concrete conduit [3]. Poor durability and unexpected service-life reductions of OPC concrete are often associated with its calcium-rich cement chemistry [4]. While calcium provides beneficial mechanical properties, oftentimes calcium is the culprit for its durability

shortcomings. In acidic environments, deterioration results from both an electrophilic attack on the calcium-based binder and reaction of the conjugate base with soluble calcium, forming gypsum, ettringite, or calcium acetate, depending on the acid (i.e., acetic acid, sulfuric acid).

In addition, OPC production is a carbon- and energy-intensive process. The calcination of raw materials alone to produce OPC accounts for 5% of the global CO₂ emissions [5], [6]. The emissions associated with the production of OPC can be divided into two categories: (1) process and (2) energy emissions. Process emissions, resulting from the calcination of raw materials produces, CO₂ on the order of 1.46 ± 0.19 Gt in 2016. Energy emissions are those associated with the combustion of fossil fuels to calcine the raw materials to well over 1000 °C. These emissions are accounted differently, depending on the reliance of fossil fuels by individual cement producers. Further exacerbating the environmental impacts of OPC, the demand for cement and concrete is expected to increase due to increasing global population and urbanization patterns. As a result, global cement production is expected to grow by 12-23% by 2050 from the current level [7].

Viable alternative construction materials are needed in order to circumvent both durability and sustainability issues associated with OPC concrete. As previously discussed, in unique environments, the use of OPC concrete has resulted in the use of additional materials and unexpected reductions of service life. In 2018, the Cement Sustainability Initiative (CSI), an organization formed by a global consortium of leading cement producers, and the International Energy Agency released a technology roadmap for a low-carbon transition of the cement industry. In this report, alternative construction materials are identified as potential options to lower the CO₂ emissions of the industry. However, design standardization and long-term durability studies are remaining challenges for these materials to become viable alternatives [7].

Alternative Cementitious Materials: Recent developments in alternative cementitious materials have suggested novel materials that may be viable to circumvent sustainability and durability issues associated with OPC concrete. The most promising of these alternative cementitious materials are (1) high-alumina, (2) super-sulfated slag, (3) alkali-activated, and (4) carbonate-based cements [8], [9]. These alternative cementitious material systems have demonstrated increased durability (i.e., high-temperature resistance, low shrinkage, high acid resistance) due to their alternative cement chemistries (e.g., lower calcium content). In addition, these cements often are demonstrated to generate lower CO₂ emissions during production up to 50% CO₂ reductions when compared to OPC production [9]. A 5-90% reduction in CO₂ emissions provided by alternative cements could lead to 0.25-7.2% reduction in global CO₂ emissions. These reductions could offset the recent increases of worldwide CO₂ emissions, which grew to approximately 37 Gigatons of CO₂ (GtCO₂) in 2017 [10]. Current projections show that for every 500 GtCO₂ accumulated in the atmosphere, global temperatures are projected to increase between 1.4-2.8 °C, and sea-levels will rise meaning that a yearly reduction of 0.1-2.664 GtCO₂ could help delay the effects of continued CO₂ accumulation. Moreover, the decreased CO₂ emissions from alternative cements could reduce urban warming in the world's three largest cement producers: China, India, and the United States. Emission reductions can effectively slow down the temperature increase in urban areas, which has led to increased use of cooling air conditioning systems [11], [12].

Despite these environmental benefits, the implementation of these alternative cements are hampered by (1) durability gaps in knowledge, (2) high product variability, and (3) lack of complete life cycle assessments that substantiate environmental benefit compared to OPC. The aforementioned challenges are active and high-impact areas of global research and development.

Scope of Work: The aim of this paper is to provide a general classification, overview, and future outlook of the most promising alternative cementitious materials, which may constitute significant classes of next-generation of construction materials. Specifically, this review details general information about each cementitious binder, its mechanical properties, potential environmental benefits, and case studies that highlight real-life applications of these systems. For more detailed information on sustainable cement production, see the following review [13].

Table 1. Summary of aluminum-rich alternative cement chemistries and properties, general classification, and state-of-the-knowledge. Additional references used in the table include: CAC references: [14]–[17], [15]; CSA references: [18]–[20]; CSAB references: [21], [22].

	High-Aluminate Cements		
Classification	Aluminum-rich Cements		
Abbreviation	CAC	CSA	CSAB
Sub-category	Calcium Aluminate Cement	Calcium Sulfoaluminate Cement	Calcium Sulfoaluminate Belite Cement
Type of Precursor	Pyro-processed calcium and alumina mineral phases	Pyro-processed calcium and alumina mineral phases	Pyro-processed calcium and alumina mineral phases
Type of Activation	Hydraulic (water-induced dissolution of precursor)	Hydraulic (water-induced dissolution of precursor)	Hydraulic (water-induced dissolution of precursor)
Type of Binder	Calcium aluminate hydrate phases (CAH ₁₀ , C ₂ AH ₈)	Calcium aluminosulfate hydrate (C ₄ A $\hat{S}$ 12H), ettringite (AFt) and calcium aluminosilicate (C-A-S-H) phases	Calcium aluminate hydrate (C ₄ A $\hat{S}$ 12H), ettringite (AFt), calcium aluminosilicate phases (C-A-S-H), and calcium silicate hydrate (C-S-H) phases
Typical Water-to-Cement Ratios	0.30–0.50. ≤ 0.4 is necessary for good long-term strength.	0.26–0.8	0.35–0.5
Compressive Strengths (psi)	8,000 psi at 24 hours	6,530 psi to 8,480 psi at 24 hours (dependent on admixture usage)	6,400 psi at 24 hours and 7,970 psi at 7 days (highly dependent on water content).
Time to Initial Set with no Admixtures	3–5 hours. Set time increases with decreasing lime-to-alumina ratios (calcium content)	More than 1 hour, yet setting time is affected by clinker dissolution and kinetics of hydrate precipitation.	45 minutes for initial set.
Suppliers and Cost Unit	SECAR, CALTRA (\$2.5/lb)	CALTRA, Buzzi Unicem USA (\$0.5/lb)	CALTRA

HIGH-ALUMINATE CEMENTS

Introduction: Calcium aluminate (CA) cements are a category of high-aluminate cements that contain about 10%-40% tetracalcium aluminoferrite ($4\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{Fe}_2\text{O}_3$), and 40%-50% monocalcium aluminate (CaAl_2O_4) phases, with calcium carbonate and other impurities. It was originally developed by LaFarge (currently known as Lafarge-Holcim) in 1913. The following year, it was supplied to the French government during World War I to construct gun emplacements and utilized in times of accelerated production due to its rapid hardening properties [16]. Two additional categories of high-aluminate cements exist: calcium sulfoaluminate (CSA) cements and calcium sulfoaluminate belite (CSAB) cements. These cements incorporate a source of sulfate during the clinkering process to produce calcium sulfoaluminate phases (e.g., Ye'lemite, Ternosite), as in the case of CSA cements [20]. While similar to CSA cements, CSAB cements incorporate a higher content of belite (i.e., $2\text{CaO}\cdot\text{SiO}_2$) phases [30], [31]. An important sub-category of CSAB cements, which is not further explored herein, are Belite-Ye'eliminate-Ferrite (BYF) cements [32].

Processing and Environmental Impact: The raw materials necessary for the manufacture of CA cements are limestone (calcium source) and bauxite (alumina source). Bauxite, one of the only suitable commercial aluminates, contains about 20% ferric oxides, a necessary component. The raw materials are calcined at a temperature of 1450°C to form the aforementioned pyro-processed calcium aluminate phases [33]. Despite the high calcining temperature, researchers have reported 47% reductions in CO_2 emitted during manufacture in comparison to OPC [9], [17].

Depending on the raw material source and pyro-processing performed during clinkering, the production of calcium sulfoaluminate phases and belite has the potential to increase the CO_2 emissions of CSA and CSAB cements. However, reductions of 45%-16% have been reported when compared to the CO_2 emissions associated with OPC production [9], [30]. Further reductions in environmental impact can be maximized with novel processes as in [34] and advanced clinker processing technologies, as demonstrated in [35].

Material Properties: The main material properties of interest in CA cements are rapid setting times, strength gain, and reduced shrinkage. The water-to-cement ratio is critical for the long-term durability of this cement, as the main binding phases ($6\text{CaOAl}_2\text{O}_3\cdot 10\text{H}_2\text{O}$ and $2\text{CaOAl}_2\text{O}_3\cdot 8\text{H}_2\text{O}$) are thermodynamically meta-stable phases and undergo a process of thermodynamic stabilization named "conversion." In conversion, the binding calcium aluminohydrate phases densify to thermodynamically stable phases ($3\text{CaOAl}_2\text{O}_3\cdot 6\text{H}_2\text{O}$ and $\text{Al}_2\text{O}_3\cdot 3\text{H}_2\text{O}$), releasing water in the process and, as a consequence, increasing the material porosity. Recent studies have demonstrated that the utilization of limestone aggregates in CA cement concrete results in minimal reductions to the material compressive strength after conversion has occurred [36].

The addition of calcium sulfoaluminate phases and belite phases to produce CSA and CSAB cements permits a lesser dependence on water-to-cement ratios and reduce conversion by limiting the creation of metastable phases [32], [37], [38]. From a cementitious binder perspective, these improved material properties are imbued by the creation of calcium silicate hydrate ($2\text{CaOSiO}_2\cdot\text{H}_2\text{O}$), gypsum (CaSO_4) and ettringite ($((\text{CaO})_6\text{Al}_2\text{O}_3(\text{SO}_4)_3(\text{OH})_{12}\cdot 26\text{H}_2\text{O})$) phases [20], [30].

Current and Future Applications: Calcium aluminate (CA), calcium sulfate (CSA), and calcium sulfoaluminate belite (CSAB) cements have been implemented in various projects worldwide. For example, state route 60 West in Los Angeles, California, has CSA cement

sections that have been in place for 17 years with minimal deterioration [17]. Moreover, in Europe, CA cements have been used since the 70s as structural components for commercial and residential infrastructure. While lessons on their deterioration and failures have been collected over the years, about 30,000 to 50,000 buildings are estimated to possess in-service CA cement concrete structural members [39]. Future prospects for CA cements may lie within the burgeoning field of concrete additive manufacturing (i.e., concrete 3D printing). The fast setting of CA cements provides an opportunity to quickly and efficiently 3D print structures that need minimal to no formwork as demonstrated in [34].

SUPER-SULFATED SLAG CEMENTS

Introduction: Super-sulfated slag (SS) cements were first studied in 1909 by Kühl [40]. These cements are composed of 80-85 wt.% slag, 10-15 wt.% anhydrite, and 5 wt.% OPC [41] and is covered in the British standard: BS EN 15743:2010, with an amendment in 2015 (A1:2015) and Indian standard: IS 6909 [42], [43]. As seen in **Table 1**, activation of SS cements is most similar to that of salt-activated cements, but differ in that SS cements attain a higher pH by incorporation of OPC as a source of calcium hydroxide.

Processing and Environmental Impact: No lifecycle assessment exists to verify the CO₂ reductions associated with the manufacturing and utilization of SS cements. Despite the lack of robust environmental impact information, these cements have been suggested as a sustainable alternative to OPC since 85% of the cement is sourced from ground granulated blast furnace slag, a byproduct from the steel manufacturing process [8], [44].

However, the sustainability of SS cements is dependent on the sourcing of ground granulated blast furnace slag. In 2016, the estimated global production of ferrous and steel slag was about 600 to 460 million tons, with about 2 million tons being imported for consumption in 2016. The main importers being Japan and Canada. According to the United States Geological Survey (USGS), the supply of blast furnace slag continues to be problematic due to closure and/or idling of a number of active U.S. blast furnaces, lack of construction of new furnaces, and depletion of old slag piles. Adding to the environmental impact of this byproduct, at the end of 2016, USGS estimated that granulation cooling in the U.S. is only available at two furnaces [45]. Demand for slag is expected to increase at a compound annual growth rate of 2.7% from 2017 to 2025 due to its global use within the construction industry [46]. The high slag demands in combination with the aforementioned reductions in domestic supply yields an uncertain sustainable future and probable high environmental impact of slag-based cements. As a consequence, alternative aluminosilicate sources (i.e., volcanic rocks and sedimentary rocks) have been explored in the last decade [47]–[50].

Material Properties: As shown in **Table 1** The main hydration products are calcium silicate hydrate (C-S-H) and ettringite [51]. Such combination of binding phases allows for a very low heat of hydration and imbues the material with good chemical durability [8]. The compressive strength of SS cements is dependent on the dissolution of the slag (i.e., precursor reactivity), which can be mitigated via grinding, especially if the powder surface area is above 500 m²/kg [23], [52]. Recent durability studies have demonstrated the ability of SS cements to bind aggressive chlorides and prevent corrosion of embedded steel. However, the corrosion mechanisms of embedded steel must be further explored given the high sulfate content in the SS cement microstructure, categorized as a reductive environment [53], [54].

Current and Future Applications: SS cements have been produced and used in many European countries for more than 50 years due to their chemical durability. The main

applications of SS cements include seawater civil engineering projects, concrete pipes, and structural components for chemical processing plants. However, recent decreases in slag reactivity have reduced the implementation of these cements. In the current decade, a higher reactivity and commercial SS cement (Slagstar®) has been produced by the Wopfinger Building Materials Group, a privately owned Austrian company. This commercial SS cement has been implemented in more than 100 projects, as reported by the company in 2009 [55], [56].

Table 2. Summary of silicon-rich alternative cement chemistries and properties, general classification, and state-of-the-knowledge. Additional references used in the table include:

SS cements references: [23], [24]; Salt-activated cements references: [25]; Low-calcium AACs references: [26]–[28]; High-calcium AACs references: [29].

	Super sulfated Slag Cements	Alkali Activated Cements	
Classification	Silicon-rich Cements		
Abbreviation	SS	AAC	
Sub-category	-	Salt-activated cements	High-Calcium AACs
Type of Precursor	Non-processed aluminosilicate powders often sourced from industrial waste streams	Non-processed aluminosilicate powders often sourced from industrial waste streams	Non-processed aluminosilicate powders often sourced from industrial waste streams
Type of Activation	Sulfate-based (anion) dissolution occurring at high pH values due to addition of 5% OPC or hydrated lime (CH).	Sulfate or Carbonate-based (anion) dissolution occurring at pH values between 12.6-7.0.	pH-based dissolution occurring at pH values between 13-14. Additional silica supplements may be used.
Type of Binder	Calcium silicate hydrate (C-S-H) and ettringite (AFt)	Sodium Calcium Aluminosilicate Hydrate (C-N-A-S-H)	Calcium Aluminosilicate Hydrate (C-A-S-H) and Calcium Silicate Hydrate (C-S-H)
Typical Water-to-Cement Ratios	0.25-0.5	0.31-0.61	0.2-0.48
Compressive Strengths (psi)	430 psi to 1450 psi at 24 hours and 2750 psi to 4300 psi at 7 days (dependent on slag reactivity)	726 psi to 5650 psi at 3 days	2,900 psi to 8,700 psi at 3 days (dependent on activators and precursor used)
Time to Initial Set with no Admixtures	225 minutes	40 minutes to 455 minutes	50 minutes to 250 minutes (dependent on activators and precursor used)
Suppliers and Cost Unit	NA	ARC Innovations (South Africa) Hybrid Cement	NA

ALKALI-ACTIVATED CEMENTS

Introduction: The theoretical basis and development of alkali-activated materials were

developed by Ukrainian scientist, Victor Glukhovsky, in 1959 [57]. Alkali-activated cements (AACs) utilize either natural or artificial aluminosilicate materials (e.g., coal fly ash, metakaolin clay, blast-furnace slag) to produce a variety of binder via the use of activating solutions [58]. Differences in precursors and activating solution chemistries gives rise to three main sub-categories of AACs, these are (1) high-calcium AACs, (2) low-calcium AACs, and (3) salt-activated cements.

Table 3. Summary of carbonate-rich alternative cement chemistries and properties, general classification, and state-of-the-knowledge.

	Carbonate-based Cements		
Classification	Carbonate-rich Cements		
Abbreviation	CC		
Sub-category	Mineral Carbonate Systems		Biogenic Carbonate Systems
Type of Precursor	Pyro-processed calcium-silicate minerals (CS, C ₃ S ₂) at temperatures of 1200 °C.	High-salt solutions (i.e. brine)	Urea and presence of calcium ions
Type of Activation	High CO ₂ concentrations in solution	High-pressure CO ₂ gas	Conventional (i.e. S. Pasteuri) or engineered (i.e. E. coli) bacteria
Type of Binder	Calcium carbonate and silica gel	Calcium carbonate polymorph stabilized	Calcium carbonate polymorph precipitation
Typical Water-to-Cement Ratios	0.37	Varies via CO ₂ concentration	Varies by bacterial media
Compressive Strengths (psi)	>10,000 psi at 24 hours.	N/A	N/A
Time to Initial Set with no Admixtures	Varies depending on CO ₂ curing procedure. Currently available as pre-cast members.	Varies depending on CO ₂ curing procedure.	Depends on bacterial culture, and rate of precipitation.
Suppliers and Cost Unit	Solidia Technologies	Calera	NA

Processing and Environmental Impact: AACs are often considered low-CO₂ materials since they can utilize aluminosilicates from industrial waste streams (e.g. coal fly ash, slag). These precursors are often activated with highly alkaline activating solutions composed of sodium hydroxide and, oftentimes, dissolved sodium silicates. The use of such activating solutions accounts for 59% of the CO₂ emissions associated with the production of AACs [59]. Thus, activation of aluminosilicate precursors with salts (e.g., sodium carbonate, sodium sulfate, calcium sulfates) has the potential to reduce further the CO₂ emissions of these materials. Moreover, it has been suggested in recent studies that the required activating salts can be sourced from existing industrial waste streams [60]. As a result, in addition to their similarity with SS cements, this review has separated these salt-activated cements in their own sub-category. Lastly, the environmental impact of AACs is often determined by the aluminosilicate source location, energy source, and mode of transportation used throughout the manufacturing process. Depending on these factors, ACCs can achieve 80-97% reductions in CO₂ emissions compared to

OPC [61], [62]. Thus, the implementation of AACs can reduce the CO₂ emissions associated with concrete production by a factor of four [63].

Material Properties: As seen in **Table 2**, AACs can produce different binder types dependent on both the aluminosilicate precursor and activating solution. Thus, the mechanical and general material properties can vary widely depending on the material formulations and mixture proportions [61], [64], [65]. In general, AACs offer increased durability, as demonstrated in recent studies that have identified the satisfactory performance of ACCs under sulfate attack, seawater environments, acidic media, alkali-silica reaction, steel corrosion, and fire [66]. In addition, these cements have been demonstrated to also have high compressive strength gain, good abrasion resistance, low shrinkage, and high resistance to deicing salts [61].

Current and Future Applications: AACs have been used globally in a wide array of infrastructure projects. In the United States, pavements have been constructed with AACs and demonstrated to have adequate performance in service [17]. Banah CEM (UK), Zeobond (Australia), and Milliken's GeoSpray (USA) are global producers of AAC material products. Banah CEM provides AAC precast materials and cinderblocks. These products are marketed for their superior fire and acid resistance. In the last two years, Milliken's GeoSpray has been utilized to rehabilitate a small hydroelectric facility in Auburn, New York, using more than 400,000 pounds of AAC mortar and to repair 2,800 feet of sewer in Bloomington, Illinois. The main challenge in the widespread implementation of these cements, in addition to the environmental challenges aforementioned, is the (1) relative variability of aluminosilicate precursors derived from industrial waste streams; (2) lack of mechanistic understanding of durability and degradation processes; (3) application technicalities, such as sensitivity to water content and use of caustic activating solutions; and, (4) lack of standards to progress knowledge-based material selection methodologies.

CARBONATE-BASED CEMENTS

Introduction: Carbonate-based cements generally rely on the presence of calcium, carbonate, and bicarbonate ions in solution to reach oversaturation levels and, subsequently, precipitate calcium carbonate—a thermodynamically stable calcium-based mineral. These cementitious systems are limited by calcium ion availability, which can be provided by either (1) water-unstable (i.e., pyro-processed) calcium-silicate minerals or (2) available aqueous calcium ions. Secondly, in order to form calcium carbonates, CO₂ is used to raise the alkalinity of water. CO₂ availability can be achieved by either (1) injection from industrial waste streams or (2) bacterial mechanisms (e.g., urease enzyme breakdown of urea). The increase in alkalinity, when met with sufficient calcium, permits the of calcium carbonates, as seen in **Table 3**.

However, the cementitious mechanisms of calcium carbonate have not been fully established. Recent investigations indicate that possible binding mechanisms may consist of calcium carbonate polymorph stabilization (i.e. vaterite → aragonite network), microstructure filling via nucleation growth, or micro-sized reinforcement [67]–[71]. As a result, the review herein classifies two main categories of carbonate-based systems: (a) mineral carbonate and (b) biogenic carbonate systems.

Processing and Environmental Impact: Two main process technologies exist within the category of mineral carbonate systems. The first technology involves calcination of calcium-silicate minerals (CaO·SiO₂ and 3CaO₂·SiO₂) to 1200 °C (pyro-processing) to impart thermodynamic instability in the presence of water. It is well known that the high-temperature calcination of calcium-silicate minerals results in vitrification at temperatures above 800 °C [72].

Such vitrification process yields thermodynamically unstable phases, which in contact with water, permit calcium ion availability. Concomitant injection of CO₂ gas allows for an increase in the water's alkalinity and results in precipitation of calcium carbonate. Thus, the sequestration of CO₂ via calcium carbonate formation yields a CO₂ reduction of up to 70% when compared to emissions from OPC production [73]. In addition, according to the curing process utilized by the producer of these mineral carbonate cement, between 70%-80% of water can be recovered, further decreasing the environmental impact of these cements [74]. The second process technology utilizes calcium ion-rich waters (i.e., brines) or electrochemical processes (i.e., ABLE: "Alkalinity Based on Low Energy" processes) to permit calcium ion availability, followed by CO₂ gas injection to precipitate calcium carbonate products [75]. The environmental impact of this product has seldom been assessed, yet Calera, a California-based company proprietor of this technology, has reported sequestration of up to 90% of CO₂ from a 10MW-equivalent power plant with a net energy penalty of about 5% to 10%. However, the environmental impact of such a process is highly dependent on the sourcing of brine or calcium-rich waters, as aforementioned.

Biogenic carbonate systems utilize conventional (i.e., *Sporosarcina pasteurii*) or engineered (i.e., *E. coli*) bacteria that produce the urease enzyme, which is able to consume urea and increase the alkalinity of the surrounding aqueous medium [70]. Calcium ion availability is often provided by the use of OPC or incorporation of a calcium salt. As a result, this bacteria-mediated system can precipitate calcium carbonate without the need for injection of CO₂, utilization of brine, or pyro-processing of calcium-silicate phases. Nucleation and calcium carbonate growth permit the cementation of adjacent fissures or unbound sand grains in mortars and concretes [68]. However, significant limitations of these system exist given their environmental impact due to waste ammonium production. Furthermore, life-cycle assessments must be conducted to confirm the overall sustainability of these cements [76].

Material Properties: Table 3 lists material properties for carbonate-based systems, which vary widely. Mineral carbonate systems have been reported to achieve compressive strengths of more than 10,000 psi in less than 24 hours, while biogenic carbonate systems vary widely depending on the bacterial species, media, and specific application. For example, compressive strengths between 21 psi (soil stabilization application) to ~9,500 psi (as a crack sealant in OPC systems) [77] have been reported.

Current and Future Applications: Biogenic carbonate systems have had important advancements towards field-scale experiments. Field-scale experiments have been implemented to assess the feasibility of soil and structural foundation stabilization [78]. Furthermore, new research has produced structural cylinders capable of withstanding compressive strengths of 800 psi [79]. Over the next few years, much improvement in the advancement of carbonate-based systems is anticipated due to their unique capacities to leverage living bacteria and sequester carbon dioxide.

CONCLUSIONS

This review presents an updated general classification and overview four promising alternative cementitious material groups: (1) high-aluminate, (2) super-sulfated slag, (3) alkali-activated, and (4) carbonate-based cements. These promising alternative cements offer environmental benefits in their production and significant durability advantages, when compared to conventional OPC concretes. The main conclusions from the herein literature review are:

- Fast-setting high-aluminate cements can provide a material to improve additive

manufacturing.

- Super sulfated slag cement offer increased durability in terms of both acid attack, and chloride induced steel corrosion.
- Depending on aluminosilicate high-resource availability, AACs may provide an opportunity to increase local resource utilization and solve significant infrastructure challenges.
- Carbonate-based cements provide an opportunity to sequester carbon dioxide and to creating living infrastructure.

It is apparent from the reviewed literature that all alternative cementitious materials have material properties of interest to the construction industry and that most of these materials have been used in projects for several decades. However, their widespread implementation is often hampered by (1) precursor variability; (2) lack of mechanistic understanding of durability and degradation processes; (3) application technicalities, such as sensitivity to water content and use of caustic activating solutions; (4) lack of standards to progress knowledge-based material selection methodologies; (5) absence of robust life-cycle assessments; and (6) uncertain full-scale economic considerations – areas that should receive attention from academics and practitioners alike.

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