Alternative Cementitious Materials for Increased Concrete Durability

Science and Technology Program

Research and Development Office

Final Report No. ST-2022-19142-01

U.S. Department of the Interior September 2022

REPORT DOCUMENTATION PAGE					*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE ***(DD-MM-YYYY)*** September 30, 2022	**2. REPORT TYPE** Research	**3. DATES COVERED** *(From - To)* December 2019-September 2022

4. TITLE AND SUBTITLE Alternative Cementitious Materials for Increased Concrete Durability	**5a. CONTRACT NUMBER** XXXR4524KS-RR4888FARD1904601 / F074A
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 1541 (S&T)
6. AUTHOR(S) Catherine Lucero, P.E.	**5d. PROJECT NUMBER** Final Report No. ST-2022-19142-01
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Concrete and Structural Laboratory, Technical Service Center US Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007	**8. PERFORMING ORGANIZATION REPORT NUMBER** 8530-2022-29
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Science and Technology Program Research and Development Office Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007	**10. SPONSOR/MONITOR'S ACRONYM(S)** Reclamation **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** Final Report No. ST-2022-19142-01

12. DISTRIBUTION/AVAILABILITY STATEMENT
Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The production of durable and long-lasting concrete is essential for Reclamation structures. Materials such as ASTM C150 cement and Class F Fly Ash have been proven for decades to produce quality concrete. Recent changes to environmental policy and new sustainability goals within the concrete industry has led to changes in the types of materials available to produce concrete. With these changes comes uncertainty on the ability to produce quality concrete. This report summarizes available alternative cementitious materials and supplementary cementitious materials. It compares the fresh and hardened properties of concrete made with these materials. It also identifies the relevant ASTM documents that can be used to test and specify these materials.

15. SUBJECT TERMS
Concrete durability, concrete sustainability, portland limestone cement, fly ash

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT U	**b. ABSTRACT** U	**THIS PAGE** U	U		**19b. TELEPHONE NUMBER** *(Include area code)*

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Acknowledgements

The Science and Technology Program, Bureau of Reclamation, sponsored this research.

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Final Report No. ST-2022-19142-01

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Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology Program

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Acronyms and Abbreviations

AA	Alkali-Activated
AAFA	Alkali-Activated Fly Ash
AAS	Alkali-Activated Slag
ACI	American Concrete Institute
ACM	Alternative cementitious material
ASCM	Alternative Supplementary Cementitious Materials
ASR	Alkali Silica Reaction
CAC	Calcium Aluminate Cement
CKD	Cement Kiln Dust
CO_2	Carbon Dioxide
CSA	Calcium Sulfoaluminate Cement
GSA	General Services Administration
OPC	Ordinary Portland Cement
PCA	Portland Cement Association
PLC	Portland Limestone Cement
Reclamation	Bureau of Reclamation
SAI	Strength Activity Index
SCM	Supplementary Cementitious Materials
USBR	Bureau of Reclamation
w/cm	water-to-cementitious materials ratio

Contents

Page

Executive Summary

The production of durable and long-lasting concrete is essential for Reclamation structures. Materials such as ASTM C150 cement and Class F Fly Ash have been proven for decades to produce quality concrete. Recent changes to environmental policy and new sustainability goals within the concrete industry has led to changes in the types of materials available to produce concrete. With these changes comes uncertainty on the ability to produce quality concrete.

The immediate change to the landscape has been the nationwide production of portland limestone cements in place of ordinary portland cement. Portland limestone cement produced now has been engineered to have similar properties to ordinary portland cement. Testing performed by Reclamation as well as a considerable amount of research from other government agencies and academia has shown that portland limestone cement performs similarly to ordinary portland cement. In many cases, it can work synergistically to with supplementary cementitious materials to have increased durability properties. In addition to portland limestone cement, there are also other alternative cements that are available and durable in precast or repair applications.

The second imminent change is the consistent availability of quality fly ash. As power plants are decommissioned or offline more often, it may be difficult to obtain fly ash in certain regions. Fly ash suppliers have begun investigating the quality of previously disposed fly ash. With the use of beneficiation processes, harvested fly ash can meet the specified requirements of ASTM C618. Since it retains its pozzolanic activity, it has shown to be just as effective in mitigating alkali-silica reaction and resisting sulfate attack. In addition to harvested fly ash, bottom ash from the same power plants has been shown to be pozzolanic if ground to a particular fineness. These two new sources of pozzolans will be important producing quality concrete as the number of power plants continues to decline. Aside from fly ash, other promising supplementary cementitious materials are making their way into the marketplace. Ground glass now has an ASTM specification, and producers can begin recycling and processing glass to meet specifications.

This report summarizes available alternative cementitious materials and supplementary cementitious materials. It compares the fresh and hardened properties of concrete made with these materials. It also identifies the relevant ASTM documents that can be used to test and specify these materials.

Background

The impact of cement production on natural resources and energy use is significant. A large amount of energy is required to fire the kiln to appropriate temperatures to produce the clinker, and the process consumes a large amount of virgin materials. The concrete industry is focused on reducing the environmental impact of production which can be done by improvements in the portland cement production process, the incorporation of recycled materials in concrete mixtures, or proportioning concrete to reduce the amount of cement needed per cubic yard [1].

There are alternative cementitious materials (ACMs) that may offer increased durability compared to ordinary portland cement (OPC). These cements may be hydraulic or non-hydraulic and could offer longer service life in certain applications.

Supplementary cementitious materials (SCMs) are defined as materials that contribute to the properties of concrete through hydraulic or pozzolanic activity when used in conjunction with OPC [2]. Many SCMs are waste byproducts of other industries. SCMs contribute to concrete sustainability because they reduce the embodied energy and CO_2 footprint per cubic yard and improve performance and long-term durability. Reclamation has a long history with the use of SCMs beginning with the first use of fly ash in Hungry Horse Dam in the late 1940s. The use of SCMs has contributed to the longevity of Reclamation's structures for decades due to their ability to mitigate expansion due to alkali-silica reaction, the decreased porosity of the hydrated paste, and the increased resistance to sulfate attack.

Reclamation cast-in-place concrete specifications include language to address durability. In regions where there are a high concentration of sulfates in the soil, a Type V (low tricalcium aluminate) cement is required. Pozzolans used in concrete exposed to sulfates must also have an "R" factor less than 2.5 [3]. Some projects require sulfate testing in accordance with ASTM C452 [4] or ASTM C1012 [5]. In regions where locally available aggregates are reactive, Reclamation concrete specifications require a testing in accordance with ASTM C1567 to demonstrate that expansion does not exceed 0.10% with the proposed combination of cement and SCM. Concrete exposed to freezing and thawing conditions need to have an appropriate volume of entrained air. The concrete specifications also include a maximum water to cementitious ratio (w/cm) of 0.45 for areas that need to withstand harsher exposure conditions. There are also temperature requirements for mass concrete placements, so the heat of hydration may play a role in material selection for concrete. Many of these performance criteria could not be achieved without the use of SCMs in concrete. In addition to meeting performance criteria, Reclamation adheres to EPA recycled-content requirements for concrete in accordance with FAR 52-223-17 [6].

In recent years, the availability of quality materials has been limited in certain regions. Quality fly ash supplies have been reduced in part due to changes in energy production and coal power plant closures. Slag is only produced domestically in two plants, so large quantities are imported from abroad to the East and West coasts which limits the regional availability. In the Western US, there are deposits of quality natural pozzolan, but they may be underutilized by contractors if fly ash is more familiar. There have been Reclamation projects in Northern California and Western Nevada that have specified the use of fly ash for durability and temperature mitigation benefits, but concrete producers had to use different material (i.e. a Class N pozzolan) due to the lack of fly ash in the region.

There are emerging alternative supplementary cementitious materials (ASCMs) or alternative sources of SCMs (such as landfilled fly ash) that can produce durable, quality concrete. There have been recent significant advancements in testing and characterization of these materials. In the past 5 years, several ASTM test methods and specifications have been developed to allow a more widespread use of ACMs.

Cement phases referred to throughout this report follow the cement chemists' notation as follows:

A = Al_2O_3
C = CaO
$\bar{C}$ = CO_2
F = Fe_2O_3
H = H_2O
M = MgO
S = SiO_2
$\bar{S}$ = SO_3
Equivalent alkalies, $Na_2O_{eq} = Na_2O + 0.658 \cdot K_2O$
tricalcium silicate[1]: $3CaO \cdot SiO_2 = C_3S$
dicalcium silicate: $2CaO \cdot SiO_2 = C_2S$
tricalcium aluminate: $3CaO \cdot Al_2O_3 = C_3A$
tetracalcium aluminoferrite: $4CaO \cdot Al_2O_3 \cdot Fe_2O_3 = C_4AF$

Hydraulic Cementitious Materials

Hydraulic cementitious materials are binders that set and harden by chemical reaction with water and is capable of doing so underwater. Ordinary portland cement (OPC) is the most commonly used hydraulic cement used in concrete in the United States. Alternative hydraulic cements are similar to OPC, but have different raw material proportions or calcining temperatures, which may require less energy to produce. These materials also require water to hydrate.

Ordinary Portland Cement

The raw ingredients include limestone (calcium carbonate) and shale. The raw materials are heated in a rotary kiln to temperatures about 1480°C (2700°F), then cooled to produce clinker. The clinker is then ground to produce portland cement [7]. There are varying types of OPC specified by ASTM C150 [8]. These cements are designated as Type I-V with properties shown in Table 1.

[1] Tricalcium silicate, Ca_3SiO_5, in conventional notation becomes $3CaO \cdot SiO_2$ in oxide notation, or C_3S in cement chemists' notation. Simple oxides, such as CaO or SiO_2, are often written in full.

Table 1. Standard composition requirements for ASTM C150 cements *[8]*

	I	II	III	IV	V
Aluminum Oxide (AL_2O_3), max %		6.0			
Ferric Oxide (Fe_2O_3), max %		6.0		6.5	
Magnesium Oxide (MgO), max %	6.0	6.0	6.0	6.0	6.0
Sulfur Trioxide (SO_3), max %					
When $C_3A \leq 8\%$	3.0	3.0	3.5	2.3	2.3
When $C_3A > 8\%$	3.5		4.5		
Loss on Ignition, max %					
When limestone is not an ingredient	3.0	3.0	3.0	2.5	3.0
When limestone is an ingredient	3.5	3.5	3.5	3.5	3.5
Insoluble Residue, max %	1.5	1.5	1.5	1.5	1.5
Equivalent Alkalies	Report Only				
C_3S, max %				35	
C_2S, min %				40	
C_3A, max %		8	15	7	5
Tetracalcium aluminoferrite plus twice the tricalcium aluminate ($C_4AF + 2(C_3A)$), or solid solution ($C_4AF + C_2F$), as applicable, max, %					25

The primary phases formed by the reactions between portland cement and water are calcium silicate hydrate (CSH), calcium hydroxide (CH), trisulfoaluminate hydrate aka ettringite ($C_6A\overline{S}_3H_{32}$), monosulfatealuminate hydrate aka monosulfate ($C_4A\overline{S}H_{12}$), tetracalcium aluminate hydrate (C_4AH_{13}), calcium aluminoferrite hydrate ($C_6(A,F)H_{12}$), and Water (H). The strength and other properties of hydrated cement are due primarily to CSH. CH is soluble and can contribute to additional porosity in hydrated cement paste [2].

Type I and Type II are considered general use cement. Type II has moderate sulfate resistance due to the limit on C_3S. Type III cement is high-early strength cement and is usually ground significantly finer than Type I or II cements. Type V cement has high sulfate resistance with the most stringent limits on C_3A and SO_3. Type IV cement is a low-heat cement historically used for dams, but they have not been regularly produced for decades in many areas.

Portland Limestone Cement

Portland Limestone Cement (PLC) is specified as Type IL cement under ASTM C595 [9]. PLCs are produced by grinding up to 15% limestone with clinker. The additional limestone is usually finer than the ground clinker which improves the particle size distribution of the blended cement. The fine limestone also acts as a nucleation site for enhanced cementitious hydration. For many concrete mixtures, PLC has similar strength and performance compared to OPC concrete [7] [10].

The Portland Cement Association (PCA) has identified using PLCs as a path toward carbon neutrality in concrete construction [11]. It is an existing lower-carbon blend and its widespread use will reduce clinker consumption and decrease emissions. In recent years, many cement suppliers have reduced or eliminated production of ASTM C150 cements and are now producing PLCs.

The cumulative heat of hydration of PLCs is typically 1 to 8% lower than OPC using the same clinker. This indicates that the two binders have undergone a similar extent of reaction during the 7-day period [10]. Tests performed by USBR, shown in Figure 1, are similar to published research.

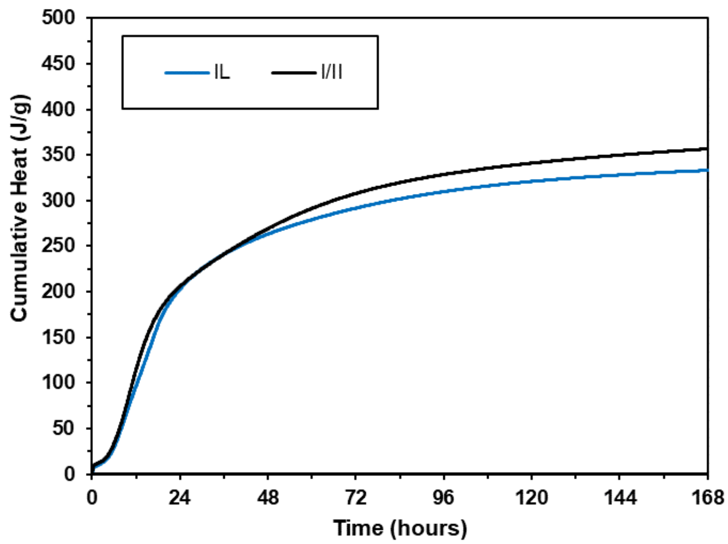

Figure 1. Cumulative heat of hydration of Type IL and Type I/II cement from the same cement plant (USBR).

Compressive strength of PLC is similar to that of OPC [10] [12]. Mortars tested at Reclamation show similar trends comparing OPC and PLC from the same plant. Type I/II cement from a source was used in mix design evaluations until the plant converted to Type IL production. The new cement was then sent to Reclamation for qualification. The results for mortar cubes tested in accordance with ASTM C109 [13] are in Figure 2. In general, PLC has been recommended to be replaced 1:1 in mixtures proportioned with OPC to get similar strengths.

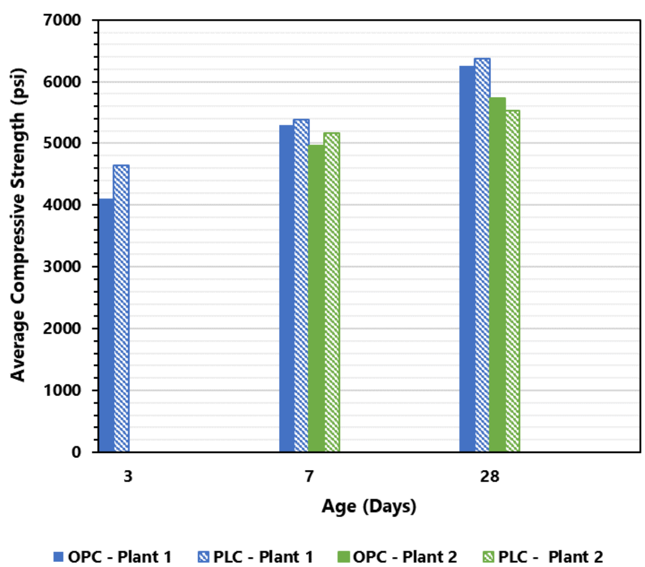

Figure 2. Compressive strength of mortar cubes made with OPC and PLC (USBR).

Drying shrinkage is similar between concrete containing OPC and comparable PLC mixtures. Concrete containing 35% fly ash was tested in general accordance with ASTM C157 [14] by Reclamation and shown in Figure 3. The PLC had a slightly higher rate of shrinkage within the first 14 days of drying, but ultimately the 28-day shrinkage was essentially the same for a comparable mix using OPC.

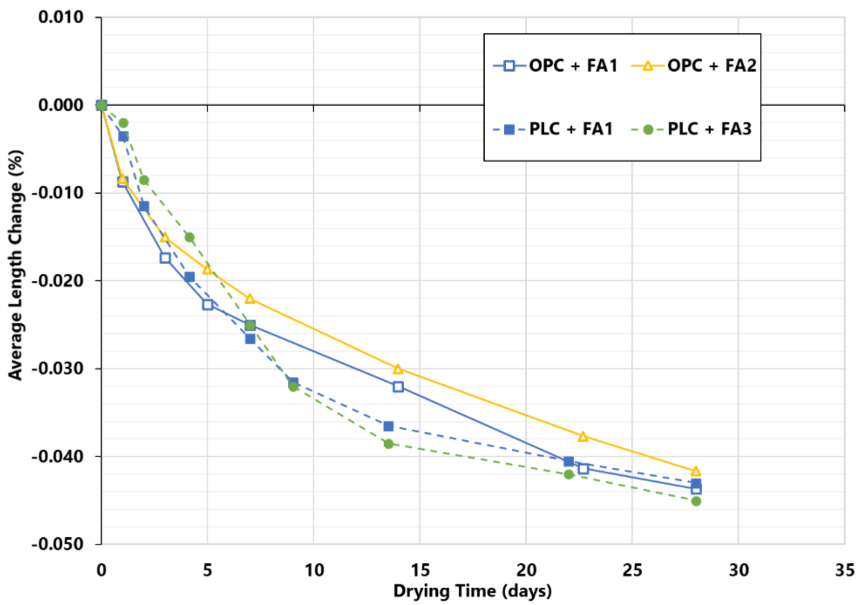

Figure 3. Drying shrinkage tested in accordance with ASTM C157 for concrete with OPC or PLC and three sources of fly ash (USBR).

Other durability properties such as sulfate resistance and ASR mitigation have been reported as similar or improved with the use of PLC compared to OPC, especially with the addition of SCMs such as fly ash and slag [15, 16, 17, 18]. Most published research has been with concrete containing up to 25% fly ash or up to 50% slag. It is not uncommon for mass concrete to contain up to 35% fly ash or 75% slag in Reclamation projects. The need for additional testing has been acknowledged and additional testing and research is forthcoming to confirm performance of PLCs with high volumes of SCMs.

Calcium Aluminate Cement

Calcium aluminate cements (CAC) were developed in the early 1900s as an effort to create a sulfate resistant cement [19]. The first field applications were by the French military during World War I [20]. These special cements contain primarily aluminates and calcium with small amounts of ferrite and silica. They are generally divided into three groups based on alumina and iron oxide contents as shown in Table 2 [7]. The main hydration products are C_3AH_6 and AH_3. The setting time is very rapid, and the reaction produces a significant amount of heat. Compared to OPC, CAC has higher early strengths. Concrete produced with CAC has good sulfate and alkali-silica reaction (ASR) resistance. It also has excellent abrasion resistance.

Table 2. Chemical composition and property ranges for calcium aluminate cements.

	Low Purity	**Intermediate Purity**	**High Purity**
Al_2O_3, %	39 to 50	54 to 66	70 to 90
Fe_2O_3, %	7 to 16	1 to 3	0 to 0.4
CaO, %	35 to 42	26 to 36	9 to 28
SiO_2, %	3 to 9	3 to 9	0 to 0.5
Wagner Surface, m^2/kg	140 to 180	160 to 200	> 200
Blaine Surface, m^2/kg	260 to 440	320 to 1000	360 to 1150
Vicat initial set (h:min)	3:00 to 9:00	3:00 to 9:00	0:30 to 6:00
1 day, min psi	3500	6000	2500
7 days, min psi	6000	8500	5000
28 days, min psi	7000	10000	--

The hydration process is described in Figure 4 [21]. At temperatures below 60 °F, CAH_{10} is formed from CA from a through-solution process where the anhydrous compound (CA) is dissolved in the liquid phase and the hydration product (CAH_{10}) randomly precipitates from the oversaturated solution. From there, C_2AH_8 and AH_3 are formed before the final, stable form (C_3AH_6 and AH_3) is reached. CAH_{10} tends to convert to C_3AH_6, but C_2AH_8 is always formed as an intermediate product, even at elevated temperatures [22]. This conversion process is reflected in the long-term strength of CAC concrete as shown in Figure 4 in orange. Because of this conversion, the use of CAC in load-bearing concrete structures should either be avoided or anticipated strength retrogression calculated when designing the structure [7]. The conversion of CAC concrete can be evaluated in the lab using several accelerated methods [23].

At intermediate temperatures (between approximately 60 and 160 °F), C_2AH_8 and AH_3 are formed as intermediate products.

At elevated temperatures above 160 °F, the reaction products are C_3AH_6 and AH_3. Only C_3AH_6 and AH_3 are thermodynamically stable phases, meaning they will not convert with changes in time or temperature passes.

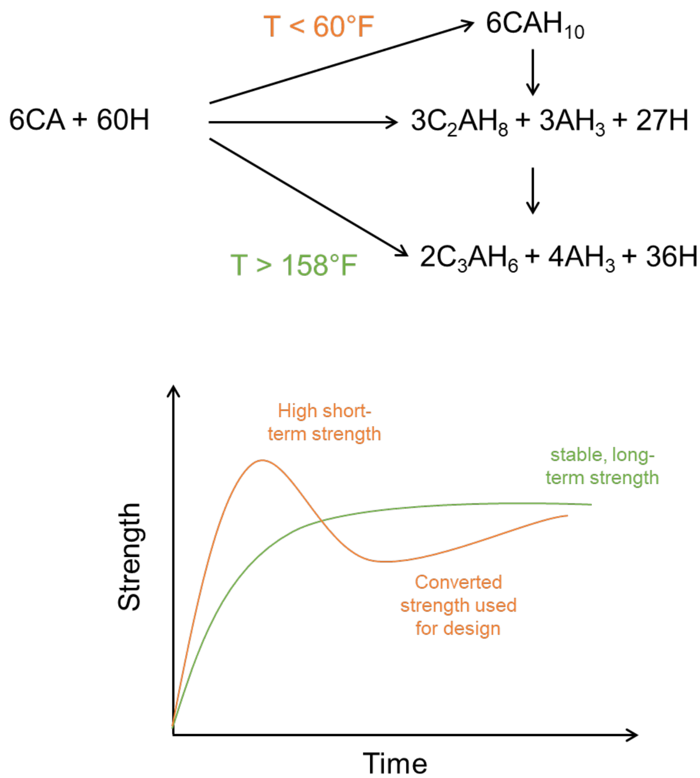

Figure 4. Hydration reaction and strength development of CAC at a w/c of about 0.40. Adapted from Scrivener [21].

Concrete mixtures using CAC generally have higher cementitious content (400 kg/m^3 or 675 lb/yd^3) and a w/c of about 0.40 or lower. The CAC concrete will appear "drier" but it will flow well under vibration [24]. Water reducers such as lignosulphonate and sodium citrate work well but may have a significant retarding effect [25]. Naphthalene and melamine superplasticizers are not very effective, however, polycarboxylate type superplasticizers can be highly effective.

While the total heat of hydration is similar to OPC, the rate of heat evolution of CAC is very high. Provisions for dissipating this heat should be considered, especially in sections greater than 6-in in thickness according to ACI 225R-19 [7].

Shrinkage in CAC concrete is similar to that of OPC concrete, however since the reaction occurs more rapidly, the shrinkage occurs over a much shorter period of time and can lead to problems with early age cracking [26]. The formation of metastable hydrates when cured at lower isothermal conditions was linked to higher shrinkage whereas the formation of stable hydrates is linked to expansion [27].

CAC concrete has been evaluated by TxDOT. It was used for a full-depth replacement of continuously reinforced concrete pavement on Texas State Highway 45. Some test sections have been in place for about 5 years and have generally shown good performance. However, some sections required repairs after 1 or 2 years but it has yet to be determined whether the distress was due to surface preparation, construction, or the CAC concrete itself [23].

In 2008, CAC concrete was used to replace significant portions of I-90/94 in downtown Chicago. CAC was chosen for its high early strength – the road was reopened within 5 hours after the start of the construction repairs. The Illinois DOT contributes the good results to experienced contractors with "top notch" placement equipment.

Figure 5. Pavement repairs using CAC concrete have shown good performance after 5 years in Chicago [28].

Calcium Sulfoaluminate Cement

Calcium Sulfoaluminate (CSA) cements were first developed in the 1960s. There are two main types that are currently produced: sulfo-aluminate clinker based or ferro-aluminate clinker based. They are not widely used in the US and Europe, but have been produced, used and standardized in China for about 30 years. Applications in China include concrete bridges, pipes, precast beams and columns, prestressed concrete elements, and shotcrete [27]. CSA cements produce ettringite and aluminum monosulfate phases that are able to bind heavy metals. This makes CSA cements suitable for hazardous waste encapsulation.

The production of CSA releases less CO_2 because the kiln requires lower temperatures for calcination compared to OPC clinker [29]. CSAs contain C_2S (belite), C_4AF (ferrite), C_4A_3 (ye'elimite) and CH (gypsum). Like in OPC, the hydration of C_2S will result in CSH and CH (portlandite), and the hydration of C_4AF will result in ettringite or calcium monosulphoaluminate. In pure water, ye'elimite yields $C_4A{\cdot}H12$ (monosulfate) and AH_3 (aluminum hydroxide).

The hydration of ye'elemite and gypsum yields either ettringite alone or a combination of ettringite and monosulfate if the amount of gypsum is reduced [30]. The ettringite produced in these reactions are not expansive and results in high early strength. Aluminum hydroxide is also formed as a hydration product. In the presence of lime, an expansive form of ettringite is the sole reaction product [20].

$$4C_4A_3\overline{S} + 2C\overline{S} + 38H \rightarrow C_6A\overline{S}_3H_{32} + 2AH_3$$

In the presence of lime, expansive ettringite formation:

$$C_4A_3\overline{S} + + 6CH + 8C\overline{S} + 90H \rightarrow 3C_6A\overline{S}_3H_{32}$$

Figure 5. Hydration of CSA cements without and with the presence of lime [30].

The initial set of CSA cement is less than 20 minutes without the use of retarding admixtures. Citric or tartaric acid retarders can be used to increase working time. The high early strength is given by the ye'elimite hydration, whereas the middle and long-term strength given by belite and ferrite hydration. As shown in Figure 6, mortars made with CSA cement develop compressive strength of at least 6000 psi within 3 days [31, 32, 33].

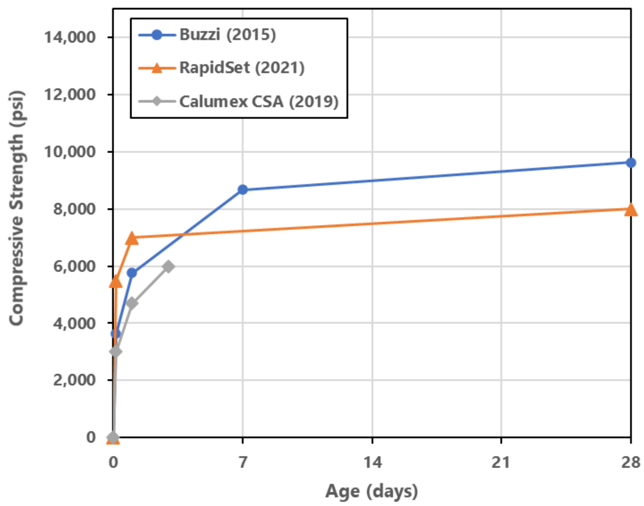

Figure 6. Strength development of CSA mortars of commercially available products.

CSA cements have a high resistance against chemical attack including seawater, sulfates, chlorides, magnesium, and ammonium salts. The high resistance is in part due to the dense pore structure developed by CSA cements [34]. Carbonation depends on the w/c and appears to be more rapid than in OPC concrete. This leads to a decomposition of ettringite as well as moderate strength loss. The alkalinity of the pore solution is about 1pH unit lower than OPC (around 9.5 to 10.7 compared to around 13 in OPC). The lower alkalinity reduces the risk of alkali-silica reaction (ASR) [27]

The following case studies are summarized from the FHWA Exploratory Advanced Research TechBrief on ACMs [28].

The California State Route 60W to State Route 71S interchange near Pomona, CA was constructed in 1997. The pavement was constructed using a commercially available ACM which was comprised of 85% CSA and 15% OPC binder. The pavement has been in service for 17 years and is still in very good condition with occasional spalls noted at the joints (Figure 7).

Figure 7. The Route 60W/71S interchange shows good performance with minor surface wear and joint spalling [28].

The California State Route 60E to State Route 71N interchange near Pomona, CA was also constructed in 1997 from a 100% CSA binder concrete. The pavement required grinding after placement, possibly due to a rapid setting time that prevented proper finishing. Aside from the grinding, the pavement is still in good condition (Figure 8).

Figure 8. The Route 60/E/71N interchange is still in good condition despite surface wear [28].

Twenty-eight miles of US Interstate 10 were placed in 1999 with a 100% CSA binder. The slabs show evidence of damage including joint deficiencies and spalls. It was noted that there was also mid-panel and corner cracking in many slabs including OPC concrete, which indicated that the CSA did not contribute to the damage. Caltrans attributed damage to subgrade deficiencies and a slab thickness that is too low for current traffic loads.

Forty miles of the Pomona Highway (California SR 60) were constructed in 2012 using a 100% CSA binder. The pavement was designed for high traffic loads with an increased slab thickness and doweled joints. The pavement was intentionally ground after placement. After 1 year in use, there was some spalling at joints and extensive longitudinal and corner cracking.

Commercial Availability

OPC and PLC are available throughout the US. In general, ASTM C150 Type I/II can be found throughout the US and Type II/V is found in areas with high sulfate environments such as California. In recent years, many cement plants have converted to producing PLC in lieu of OPC. ASTM C150 cements are becoming more difficult to source in large quantities as ASTM C595 Type IL cement is becoming more common.

CAC is readily available in the US with alumina content ranging from 40 to 80%. It is commonly used as a rapid repair material or in refractory applications. Imerys supplies calcium aluminate cements worldwide. Ciment Fondu® is available for concrete production as well as other ready-mixed mortars for various repair applications. Secar® is another option that is primarily used for refractory applications.

CSA is also available in the US. Buzzi Unicem manufactures a CSA cement in the US that can be shipped in bulk, 50 lb bags, or 2000 lb super sacks. CTS Cement manufactures Rapid Set® Cement which is available in 50 lb bags. CSA products are also produced in Europe, for example Calumex C.S.A. products are produced in the Netherlands.

Associated ASTM Standards

ASTM specifications for hydraulic cements are summarized in Table 3. There are prescriptive and performance-based specifications for OPC and PLCs. CACs and CSAs are covered in ASTM C1600 [35]. There is a “RH-CAC” type that is specifically for rapid-hardening calcium aluminate cements. The converted compressive strength is tested using a procedure in EN 14647. The rest of the cement types (ultra-rapid, very rapid, etc) can be composed of any hydraulic cement.

Reclamation cast-in-place specifications allow the use of ASTM C150 cement as well as ASTM C595 cement. Concrete repair specifications allow the use of repair materials meeting ASTM C928 [36], which could include a CSA or CAC repair mortar including aggregate.

Table 3. ASTM documents related to Hydraulic Cementitious Materials

ASTM Designation	Document Type	Document Title	Scope
C150/C150M-22	Specification	Standard Specification for Portland Cement	Standard and optional chemical composition and physical requirements for 10 types of portland cement.
C595/C595M-21	Specification	Standard Specification for Blended Hydraulic Cements	Standard and optional chemical composition and physical requirements for blended hydraulic cements for both general and special applications, using slag, pozzolan, limestone, or some combination of these, with portland cement or portland cement clinker or slag with lime.

ASTM Designation	Document Type	Document Title	Scope
C1157/C1157M-20a [37]	Performance Specification	Standard Performance Specification for Hydraulic Cement	Performance specification covers hydraulic cements for both general and special applications. There are no restrictions on the composition of the cement or its constituents. Classifies cements based on specific requirements for general use, higher early strength, resistance to attach by sulfates, and heat of hydration.
C1600/C1600M-19	Performance Specification	Standard Specification for Rapid Hardening Hydraulic Cement	Performance specification that classifies cements based on requirements for very early compressive strengths. There are no restrictions on the composition of the cement or its constituents. Standard requirements are strength, drying shrinkage, and final set. Optional requirements include sulfate expansion, ASR expansion, and heat of hydration.
C928/C989M-20a	Specification	Standard Specification for Packaged, Dry, Rapid Hardening Cementitious Materials for Concrete Repairs	Specification for repair mortars that include aggregate and any hydraulic cement.

Comparison of Hydraulic Cements

Table 4. Summary of properties of alternative non-hydraulic cements

Property	**Ordinary Portland Cement**	**Portland Limestone Cement**	**Calcium Aluminate Cement**	**Calcium Sulfoaluminate Cement**
Workability (Compared to similar OPC mixtures)	N/A	Similar fresh properties	Similar fresh properties	Similar OPC, can have high w/cm and use admixtures if required.
Curing Requirements	Moist curing	Moist curing (standard curing practices)	Moist curing or high temp steam curing for high early strengths	Moist curing (standard curing practices)
Setting Time (initial)	1.5 hr	1.5 hr (similar to OPC)	30 min to 3 hr; depending on Al_2O_3 content	< 20 min without the use of retarding admixtures
Drying Shrinkage (Concrete)	About -0.04% at 28 days	Similar to OPC	Higher early age shrinkage	About 50% less drying shrinkage
Compressive Strength (Mortar Cubes)	> 6000 psi at 28 days	6000 psi at 28 days	7000 to 10,000 psi at 28 days	> 9,000 psi at 28 days
Sulfate Resistance	Type V for sulfate resistance	Good with the appropriate amount of SCM	Excellent	Excellent
ASR Mitigation (Compared to OPC)	N/A	Similar to OPC	Excellent	Limited research available
Abrasion Resistance	Good	Good	Excellent	Limited research available
Potential Applications for Reclamation Infrastructure	All	All. Additional testing on specific mix designs may be required in concrete exposed to high sulfate environment.	Repairs to concrete where abrasion or erosion is an issue and rapid strength gain is desired. i.e. canal linings, stilling basins, outlet works	Repairs to elements where rapid strength gain is desired. Suitable for low temperature applications. i.e. canal linings, stilling basins, outlet works
Commercial Availability (as of this report date)	Type I/II or Type III available, but supply is reducing. Type II/V available in high sulfate regions. Type IV not readily available.	Available in most markets throughout the Western US	Specialty cement available as cement only or ready mix repair mortar	Specialty cement available as cement only or ready mix repair mortar

Carbonating Cementitious Materials

Carbonating cements are materials that develop strength through carbonation reactions. They are cured in a CO_2 rich environment rather than by reacting with water like hydraulic cements. These binders can be a single material or a blend of cementitious materials. There are calcium silicate, calcium hydroxide, or slag based binders. Due to the curing regime required, these materials are only applicable to unreinforced precast concrete elements like those shown in Figure 9.

Carbonated cementitious materials have a very low carbon footprint since the material encapsulates CO_2 from the atmosphere (curing chamber). Curing times may vary, but are typically about 24-72 hours. Thicker elements require longer curing times for sufficient carbonation.

The formulation of the mix design for Solidia® Cement concrete is similar to traditional concrete with the use of air entraining, water reducing and set-retarding admixtures to enhance fresh and hardened properties. With the appropriate air void system, carbonated cementitious materials can have good freeze thaw durability [38].

Figure 9. Railroad ties and pavers (solidiatech.com)

Solidia® Cement, a wollastonite/rankinite type binder has shown excellent sulfate resistance and no reaction with aggregates when tested in accordance with ASTM C227 [38].

Commercial Availability

This is an emerging technology and not fully commercialized.

Solidia® Cement is partnered with Holcim. The hardened concrete is made of carbonated calcium silicate material composed primarily of low lime-containing silicate phases such as wollastonite and rankinite. During the curing process, 1 ton of Solidia® cement can sequester up to 300 kg of CO_2. This technology has been used in precast applications such as pavers or blocks. Curing time can be under 1 day [39].

Associated ASTM Standards

There are two standards under development pertaining to carbonating cementitious materials as summarized in Table 5. They are not yet approved by ASTM. One is a specification for the cementitious material itself (i.e. the powder to be carbonated) and the other is a test method for determining compressive strength using a standardized CO_2 curing regime. There are currently limited standards associated with non-hydraulic cements.

Table 5. ASTM documents related to Carbonating Cementitious Materials (Under Development)

ASTM Designation	Document Type	Document Title	Scope
Under Development	Test Method	Test Methods for Cementitious Materials that Harden by Carbonation	Standardized mixing and curing regime for materials that harden by carbonation.
Under Development	Specification	Specification for Cement that Hardens by Carbonation	Minimum strength requirements for cements that harden by carbonation. Includes chemical and physical properties that are "report-only"

Alkali-Activated Cementitious Materials

Alkali-activated (AA) cementitious materials are also called geopolymers. Alkali-activated materials have been used in Eastern European countries as well as Finland and China.

Alkali-Activated Slag and Fly Ash

Alkali Activated Slag cement (AAS) consists of ground granulated blast furnace slag and an alkaline activator. This alternative is very eco-friendly as there is no calcination required to produce the slag, only grinding. The slag itself is a by-product of the iron industry. Fly Ash is another binder that can be activated in a similar way to slag. Class F or Class C can be used, but the calcium content affects the performance. Other materials rich in silica and alumina such as metakaolin can also be used.

Commonly used activators are sodium hydroxide (NaOH), sodium carbonate (Na_2CO_3), and liquid sodium silicate (Na_2SiO_3). Activators are introduced in small amounts, typically between 2 and 7% per weight of precursor (slag or fly ash). The activators are commonly dissolved in the mixing water prior to adding to the powder. The setting time varies with activator type and can be controlled with admixtures.

Alkali activated binders were first researched in the 1940s using slag, alkaline solutions and lime. The types of hydration products are highly dependent on the binder and activator used. In calcium rich powders (Class C ash or slag) the main hydration products are CASH, NASH, and CSH gels [27].

The strength development of AAS or AAFA cements is greatly influenced by the activator. Generally, the early strength development is quite rapid and concrete strengths after 1 day can be between 2900 and 4400 psi. Typical 28-day strengths are between 5800 and 8700 psi. There is a strong paste-aggregate bond due to the absence of the portlandite and ettringite found in OPC systems. The tensile strength has been reported to be significantly higher than OPC concrete [40].

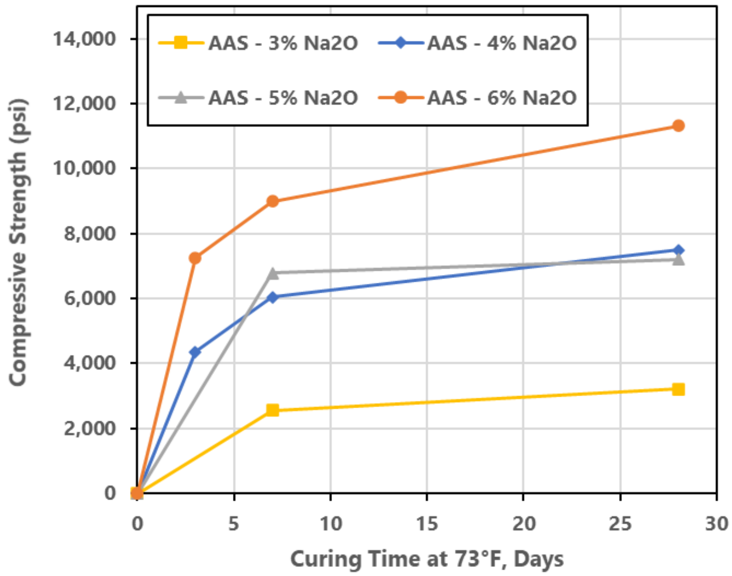

Figure 10. Compressive strength development of AAS concrete using Na_2O activator at varying concentrations, from Coelho [41] and Al-Otaibi [42].

The drying shrinkage of AAS paste is generally much higher than that of OPC paste. The high shrinkage due to moisture loss (both autogeneous and drying shrinkage) can lead to significant cracking. Glycol-based shrinkage reducing admixtures are ineffective in reducing the drying shrinkage of AAS systems. Heat curing has been shown to reduce drying shrinkage, but significant autogeneous shrinkage still occurs [43, 44]. Conversely, AAFA systems have been shown to have reduced drying shrinkage compared to OPC [45].

The water requirement of AA cements is relatively low resulting in a lower total porosity of the hardened paste. AA binders composed of various proportions and both fly ash and slag exhibit good freeze thaw resistance, which is due both to the fine pore structure and the low freezing temperature of the highly concentrated pore solution. However, in the presence of deicing salts, the concrete shows poor freezing and thawing durability. These blended alkali-activated materials are also resistant to sulfate attack and are effective at mitigating ASR [46]. Other sources indicate that AAS (slag as the sole binder) is susceptible to ASR due to the high alkalinity of the pore solution [45].

Fresh AAS or AAFA based concrete tends to be sticky and requires continuous mixing to prevent a quick slump loss and setting. The setting time depends on the reactivity of the material as well as the type and amount of activator. Portland cement can be added to the mix as an accelerator, and borates, phosphates, and copper sulfate are used as retarders.

Commercial Availability

Geopolymer concrete and repair materials are commercially available in the US. Geopolymer Solutions LLC offers proprietary dry packaged material that only requires water for mixing. The products can be supplied in super sacks, 55-lb bags or as ready mixed concrete delivery. Other companies such as Alchemy Geopolymer Solutions offer more customized solutions for each project.

Associated ASTM Standards

There is a standard test method under development for testing alkali-activated cementitious materials as summarized in Table 6. It has not yet been approved by ASTM. There are currently limited standards associated with non-hydraulic cements. Fly ash and slag should conform to their respective standards (ASTM C618 [47] and ASTM C989 [48], respectively)

Table 6. ASTM documents related to Alkali-Activated Cementitious Materials

ASTM Designation	Document Type	Document Title	Scope
New Proposed Test Method	Test Method	Test Methods for Compressive Strength of Alkali Activated Cementitious Material Mortars	Standardized mixing and curing regime for materials that react and harden with an alkali activator.

Comparison of Alternative Non-Hydraulic Cements

Table 7. Summary of properties of alternative non-hydraulic cements

Property	Carbonated Cements	Alkali-Activated Materials
Workability (Compared to similar OPC mixtures)	N/A	Generally reduced workability
Curing Requirements	Elevated temperature in CO_2 rich environment	Room temperature or higher temperatures, depending on activator and binder combination used.
Setting Time	Target strengths achieved within 24 hours, depending on size	Fly Ash – Rapid Slag – Similar to OPC or more rapid
Drying Shrinkage (Concrete)	Limited literature	Depends on formulation. High shrinkage observed in alkali activated slags.

Property	Carbonated Cements	Alkali-Activated Materials
Compressive Strength (Mortar Cubes)	About 9,000 psi at 24 hours	10,000 to 20,000 psi at 28 days depending on activator used Slag – low early strength; high later strength
Sulfate Resistance	Excellent (Solidia)	Good
ASR Mitigation	Excellent (Solidia)	Generally good, but AAS susceptible to ASR due to high alkaline pore solution
Abrasion Resistance	Limited literature	Good
Potential Applications for Reclamation Infrastructure	Precast products only. Blocks, box culverts, precast pipe, etc.	Rapid full or partial depth repairs. Applications where high acid resistance is required. Can be used anywhere OPC concrete is used.
Commercial Availability	Limited	Limited

Supplementary Cementitious Materials

Supplementary cementitious materials are in nearly all new concrete placed by Reclamation. SCMs help achieve desired concrete properties such as resistance to sulfates and mitigation of expansion due to ASR. Silica fume is another example of an SCM that may be included in concrete that is exposed to high velocity flows with sediment. SCMs are a crucial part of producing durable concrete with a long service life.

The primary SCMs that Reclamation includes in cast-in-place concrete specifications are:

- Class F Fly Ash
- Grade 100 or 120 Slag
- Class N Natural Pozzolan
- Silica Fume (for high strength or high abrasion resistant concrete)

These are considered conventional SCMs and they are well researched and have been used for decades. In some markets, supplies of conventional SCMs are becoming limited and there is a continued demand for them as contractors and owners strive to build in a more sustainable manner. Emerging sources of SCMs are becoming more relevant, and there have been significant developments in characterizing these materials for future specifications [49].

Harvested Fly Ash

Harvested fly ash is material that had been previously stockpiled in ponds or landfills. The material is recovered, treated, and can be reused in concrete. Sometimes, the fly ash was landfilled because it had a high loss on ignition (LOI) and did not meet ASTM C618 requirements., Often the fly ash was good quality, but there was insufficient demand at the time of production. Research has shown that harvested fly ash remains pozzolanic because the pH of the storage sites does not exceed 8.2, so the pozzolanic reaction cannot occur [50].

Harvested ash will likely need to be processed or benefacted prior to meeting ASTM C618 specifications. The moisture content of the ash is typically over the limit of 3.0%, so the ash needs to be dried to meet the requirement. Additionally, the LOI is usually higher than the 6.0% limit so various treatments can be implemented to lower the unburned carbon content [51]. High carbon can significantly affect the ability to entrain air. Other non-fly ash materials may be comingled in the landfill, and additional processing to remove as much of this material as possible [52]. Because of the addition of other material co-mingled with the fly ash, the harvested fly ash may need to be sieved to removed oversized material. There are several technologies employed to get the landfilled material to meet specification [53].

Average chemical and physical properties from three commercially available harvested fly ashes obtained by Reclamation for testing are summarized in Table 8.

Table 8. Chemical and physical properties of three sources of harvested and processed fly ash (USBR).

Chemical Properties	**ASTM C618 Requirement**	**Source A**	**Source B**	**Source C**
SiO_2 (%)		60.1	54.0	56.6
Al_2O_3 (%)		26.5	28.7	51.9
Fe_2O_3 (%)		5.19	8.1	5.5
Sum of Oxides	> 50%	91.79	90.8	91.7
CaO (%)	< 18%	0.9	1.3	0.8
MgO (%)		1.1	1.0	0.9
SO_3 (%)	< 5%	0.05	0.1	0.0
Total Equivalent Alkalies (%)		2.01	2.05	1.87
Physical Properties				
Moisture Content (%)	< 3%	0.1	0.05	0.06
LOI (%)	< 6%	0.8	0.72	1
#325 retained (%)	< 34%	22.5	19.71	19.43
Specific Gravity		2.28	2.33	2.26
Autoclave Expansion (%)		0.4	-0.03	-0.04
7 Day SAI (%)	> 75%	81.0	77.2	78.8
28 Day SAI (%)	< 75%	87.0	83.4	86.4
Water Requirement (%)	< 105%	99.0	97.4	98.9

Harvested fly ash maintains many of the same benefits of Class F or Class C fly ash, including its ability to suppress ASR expansion as seen in Figure 11. Mortars were tested in accordance with ASTM C1567 [54]. Mortars containing 25% harvested fly ash were able to suppress expansion below 0.10% after 14 days in NaOH [17] [55]. USBR specifications sometimes require a longer testing period of 28 days in NaOH. The harvested fly ash tested had an expansion of 0.11% after 28 days in NaOH which would not meet stringent USBR specifications, however, more fly ash (i.e. 30%) is often used in mass concrete applications and would meet the specified limit.

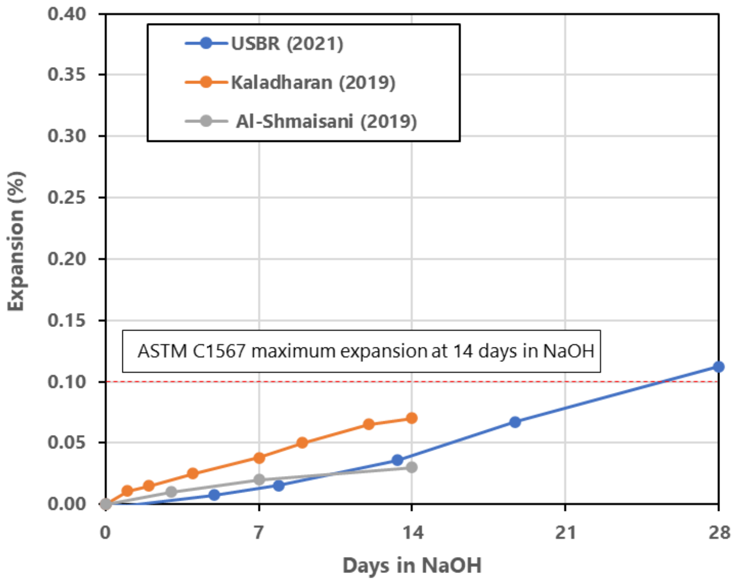

Figure 11. Alkali-silica reactivity of mortar samples containing 25% reclaimed fly ash.

It is possible for there to be a reduction in fly ash reactivity due to agglomeration and partial reaction from a long-term exposure to moisture. Fly ash reactivity can be improved by grinding, thermal processing, or chemical activation [55].

A trial batch of concrete was conducted at Reclamation using a source of harvested fly ash meeting requirements of ASTM C618. The mix contained 670 lbs of total cementitious per cubic yard with a fixed w/cm of 0.40. The non-air entrained concrete contained a #57 crushed granite and natural washed concrete sand conforming to ASTM C33 [56]. The compressive strength of the trial is shown in Figure 12. The fly ash gained strength as expected for a Class F fly ash. This is consistent with other published literature.

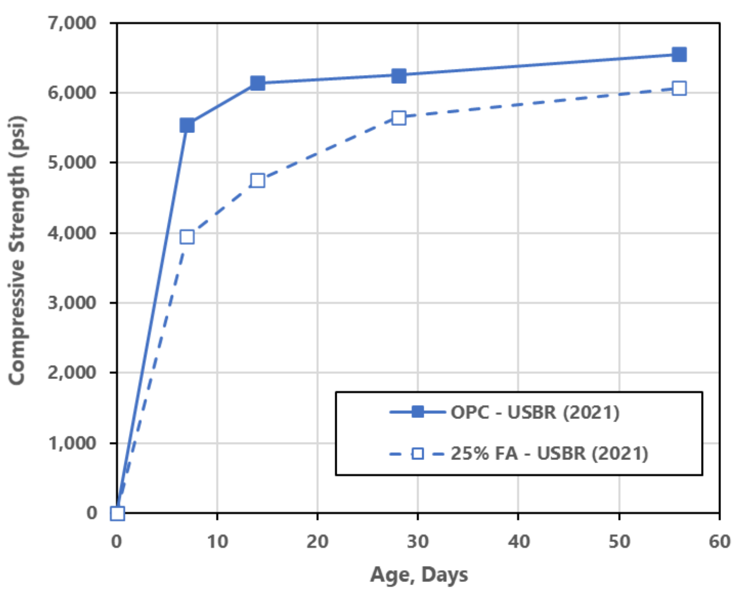

Figure 12. Compressive strength of 6-inch cylinders containing 100% OPC and 25% harvested fly ash

Bottom Ash

Coal bottom ash is the heavier, coarser particle that falls by gravity in the furnace. Since bottom ash and coal ash are formed from burning the same coal, the chemical composition is very similar. The bottom ash is much larger (about 2 or 3 orders of magnitude) and contains more crystalline phases due to the slower cooling. Bottom ash is currently used as a fine aggregate for masonry units, but research has shown that it can be minimally processed and used in concrete as an SCM. Since it currently has limited uses, a lot of it is disposed in landfills.

Unprocessed bottom ash is not very reactive, but grinding can increase the pozzolanic reactivity [57, 58]. According to Agriz et al, mortars made with ground bottom ash and fly ash from the same source did not have significant differences in compressive strength [59]. Bottom ash has been shown to be effective at mitigating expansion due to ASR using ASTM C1567 or ASTM C441 [60, 61]. With the same w/cm, the strength and durability of concrete made with bottom ash and fly ash are similar [62].

The water demand of bottom ash is greater than fly ash since it is ground and angular, whereas fly ash is spherical. Additional water reducing admixtures may be required to achieve the same slump as a similarly proportioned concrete with fly ash.

Bottom ash is sometimes co-mingled with fly ash in landfills. With processing such as grinding and screening, a comingled product could be used as an SCM in concrete.

Rice Husk Ash

Rice husks are a by-product of the rice paddy milling industry. Rice husk ash (RHA) is mostly available in developing countries where portland cement is very costly. Each ton of rice husks produces approximately 400 lbs of ash. Incineration temperatures of 930 to 1290 °F (500 to 700 °C) are required to make the ash highly pozzolanic. The specific surface area is much greater than that of cement at 20 to 50 m^2/g. Typical composition is about 90 to 95% silica, 1 to 2% alkalis and about 3 to 18% unburnt carbon.

Limited data has been published on fresh and hardened properties of concrete utilizing rice-husk ash. Many researchers compare RHA with silica fume since they have similar compositions. The particles are more porous than silica fume, which means the water demand increases significantly [63]. The workability issues can be overcome with a superplasticizer [64]. Bleeding is reduced. Like silica fume, rice husk ash does not lower the heat of hydration and would not lower the temperature rise of concrete. Generally, higher dosages of air entraining admixtures are required since the LOI is relatively high. This could lead to challenges in controlling air during concrete production.

RHA is effective at mitigating ASR at similar replacement rates as silica fume. Hasparyk et al found that a replacement of 12-15% RHA could keep expansion under 0.10% when tested in accordance with ASTM C1567 for basalt and quartzite aggregates [65]. In addition to ASR, mortars made with 10% RHA showed an 82% reduction in sulfate expansion when tested in accordance with ASTM C1012 [66]. Low w/cm concrete with 15% RHA performed well in freezing and thawing conditions [63, 66] .

Woody Biomass Ash and Co-Fired Ash

Woody biomass ash is from the combustion of 100% wood or wood waste. Wood biomass can also be co-fired with coal. It is used as raw feed for cement production in Austria, Canada, and Italy and as a "cement and concrete filler" in the Netherlands [67].

100% woody biomass ash are typically low in silica and alumina and have high LOI and do not meet ASTM C618 requirements [68, 69]. Co-fired ashes have a chemical composition that generally complies with ASTM C618 and meets SAI requirements [68]. Co-fired ash demonstrates pozzolanic reactivity as shown in bound water measurements and CH consumption [70].

Large amounts of water reducer may be required for adequate workability due to higher surface area. The ash also increased the air entraining admixture demand significantly when tested with the foam index test. ASR expansion is effectively mitigated with co-fired ashes containing lower calcium contents. Sulfate expansion is also reduced [70].

Cement Kiln Dust

Cement kiln dust is the fine-grained, solid, highly alkaline waste removed from the cement kiln exhaust gas by air pollution control devices [71]. It is comprised of unreacted raw material from clinker production and much of it is recycled back into the production process. CDK not returned is typically disposed of in a landfill or waste pile. Because CKD is made from raw materials of cement, it has a chemical composition similar to Portland cement, but with higher amounts of alkali, chloride, sulfate and free lime.

CKD has been investigated for use in concrete for decades [72]. CKD works well in ternary or quaternary systems with portland cement, fly ash, and/or slag with CDK replacing between 10-15% of total cementitious materials [73, 74]. Large replacements of CKD cause significant strength decrease, higher water demand, and increased setting time. CKD has been used in other applications, including controlled low strength material (CLSM) [71, 75]

Ground Glass Pozzolan

There are three types of recycled glass that can be used as a powder in concrete: container glass, plate glass, and e-glass. Container glass is used for glass bottle containers and is produced in different colors such as clear, green, or amber. Plate glass is clear and used for windows and windshields. E-glass is recovered from the manufacture of fiberglass reinforcements. Due to the production process, the composition of the glass is very uniform and is already regulated for toxic materials. This material is promising as an ASCM because there is a steady supply available for concrete production (about 3 million tons of recycled container glass annually [76]).

E-glass has been widely used in decorative concrete as a pozzolan for the past 10 years. The chemical composition of container glass and plate glass are similar, whereas e-glass has less SiO_2, but more Al_2O_3 and CaO. All three types of glass are considered suitable for the use in concrete. ASTM C1866 classifies two types of glass as shown in Table 9. GS is plate or container glass, and Type GE is E-glass.

Table 9. Chemical requirements of ground glass to be used as a pozzolan in concrete [77].

	Type GS	Type GE
Silicon dioxide (SiO_2), min %	60.0	55.0
Aluminum oxide (Al_2O_3), max %	5.0	15.0
Calcium oxide (CaO), max %	15.0	25.0
Iron oxide (Fe_2O_3), max %	1.0	1.0
Sulfur trioxide (SO_3), max %	1.0	1.0
Total equivalent alkalies, Na_2Oeq, max %	15.0	4.0
Moisture content, max %	0.5	0.5
Loss on ignition, max %	0.5	0.5

Several researchers have extensively studied physical and chemical characteristics of ground glass powder, as well as the effects of ground glass on fresh and hardened properties of concrete [78, 79, 80, 81]. The addition of ground glass improves workability even in ternary blends [82]. When glass is ground to a powder with 95% finer than the 325-mesh, the glass will meet all ASTM C618 performance standards. E-glass mortars with 10, 20, and 30% replacement all achieved a SAI over 100% at 28 days. In the same study, concrete mixtures with 10, 20, and 30% replacement did not lead to any significant reduction in the compressive strength, split-tensile strength, or modulus of elasticity. The addition of E-glass also improved durability including mitigating expansion due to sulfate attack and ASR, and reducing the chloride ion permeability [83].

E-glass has a much lower alkali content compared to Container and Plate glass. When tested using ASTM C1293, a 20 to 30% replacement of cement with ground E-glass powder suppresses ASR expansion similarly to a 25% Class F Fly Ash replacement. There are higher levels of alkalis in Container Glass and Plate Glass, so they are less effective at suppressing expansion from ASR. The particle size of container and plate glass influences the efficiency of mitigating ASR. In a study by Ke et al., glass particles larger than 300 μm do not contribute any mitigation effect, but smaller particle sizes (30 to 40 μm) are very effective at mitigating expansion [84].

Commercial Availability

Harvested fly ash is commercially available in several states. The products meet ASTM C618 requirements.

SEFA Group offers fly ash that has been benefacted through their STAR process which lowers the LOI to be within ASTM C618 specifications. They operate six plants throughout North Carolina, South Carolina, and Maryland.

Separation Technologies (a Titan Company) operates a full-scale pilot facility with drying and electrostatic separation technology to reclaim fly ash from surrounding coal ash impoundment basins. Brunner Island opened in 2021 to process harvested fly ash from landfills. They have had benefaction processes at Brunner Island since 2006 to remove unburned carbon to lower the LOI, but the plant now it includes drying and screening operations.

Salt River Materials Group has benefaction facilities at four plants to produce fly ash within specifications. In 2021, the Coronado plant in Eastern Arizona began harvesting fly ash from the on-site landfill. The facility can process about 300,000 tons of material per year.

Charah Solutions offers its EnviroSource benefaction technologies, which can be used for both current production and harvested ash. As of summer 2022, there are plans to benefact and recycle about 3.9 million cy of fly ash from ponds at a plant in the southeast region.

EM Technologies operates Washingtonville, PA site currently using harvested fly ash, about 2 million tons of reclaimed material is available. As of summer 2022, there are plans to harvest and beneficially use more than 9M tons of material in Georgia.

Bottom ash or co-mingled ash will likely be available as ASTM standards are created or updated to include it.

In 2021 Urban Mining Industries launched a commercial processing plant for concrete-grade ground glass. Since the adaptation of ASTM C1866, more production facilities will likely come on-line.

Associated ASTM Standards

The use of alternative sources of SCMs is usually limited by the available ASTM Standards or Specifications for materials. Traditional, standardized test methods (such as strength activity index) are not appropriate for all materials, so new test methods have been developed in recent years.

New standards include a standard specification for ground glass for use as a pozzolan, and a standard test method for measuring the reactivity of an SCM for use in concrete. A standard test method for reactivity allows new materials on the market to be tested to ensure they are reacting chemically with cement and water and are not simply adding strength through particle packing or reducing ASR expansion due to dilution.

Table 10 summarizes the ASTM Standards used to evaluate supplementary cementitious materials for use in concrete. There is a new proposed standard specification for SCMs that has not yet been approved by ASTM.

Table 10. Summary of current ASTM Standards or Specifications related to Supplementary Cementitious Materials.

ASTM Designation	Document Type	Document Title	Scope
C1709-18 [85]	Guide	Evaluation of Alternative Supplementary Cementitious Materials (ASCM) for Use in Concrete	Provides a technical approach to the evaluation of alternative supplementary cementitious materials such as pozzolans and hydraulic materials that fall outside the scope of Specifications C618, C989, and C1240
E3183-10 [86]	Guide	Standard Guide for Harvesting Coal Combustion Products Stored in Active and Inactive Storage Areas for Beneficial Use	Provides a framework for the harvesting of fly ash from landfills and impoundments.

ASTM Designation	Document Type	Document Title	Scope
C618-22	Specification	Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete	Chemical and physical requirement for Class F, Class C and Class N Pozzolan. This includes fly ash and raw or calcined natural pozzolans
C1866/C1866M-20	Specification	Ground-Glass Pozzolan for Use in Concrete	Chemical and physical requirements for recycled ground glass for use in concrete
C1897-20 [87]	Test Method	Measuring the Reactivity of Supplementary Cementitious Materials by Isothermal Calorimetry and Bound Water Measurements	Any potential supplementary cementitious material
Under Development	Specification	Standard Specification for Supplementary Cementitious Materials for Use in Concrete	Any supplementary cementitious material for use in concrete where cementitious or pozzolanic action, or both, is desired or where other properties normally attributed to an SCM is desired.

Comparison of Alternative Supplementary Cementitious Materials

Table 11 summarizes properties of concrete containing OPC and an alternative supplementary cementitious material described in previous sections.

Table 11. Summary of properties of alternative cements

Property	Harvested Fly Ash	Bottom Ash	Rice Husk Ash	Woody Biomass Ash and Co-Fired Ash	Cement Kiln Dust	Ground Glass Pozzolan
Workability (Compared to 100% OPC mixtures)	Slightly more workable	Slightly less workable, depending on particle size	Less workable	Less workable		Improved workability
Curing Requirements	Standard curing methods					
Setting Time	Slower set depending on replacement %	Slower set depending on replacement %			Greatly depends on composition	
Drying Shrinkage (Concrete)	Similar to 100% OPC	Similar to 100% OPC		Limited research available		Similar to 100% OPC
Compressive Strength (Mortar Cubes)	> 75% of control	> 75% of control	> 75% of control	< 75% of control unless co-fired		> 75% of control
Sulfate Resistance	Good	Good	Good	Limited research available	Limited research available	Good
ASR Mitigation	Good (Class F)	Good (Class F)	Good	Some have high alkali content	Some have high alkali content	Type GS has high alkali content
Abrasion Resistance	Limited literature available	Limited literature available	Good	Limited research available	Limited research available	Limited literature available
Potential Applications for Reclamation Infrastructure	Anywhere Class F fly ash is currently used	Anywhere Class F fly ash is currently used	Applications requiring high early strength or abrasion resistance in lieu of silica fume	Soil stabilization	Controlled low-strength material	Type GE glass could be used anywhere Class F fly ash is currently used
Commercial Availability	Available in select markets	Limited availability	Limited availability in the US	Limited availability	Available from cement plants	Limited availability

ACI 318 Building Code

In addition to ASTM standards, the 2019 version of ACI 318 Building Code Requirements for Structural Concrete includes new provisions for alternative cements [88]. It does not cover specifications for design criteria and performance. Any alternative material must be approved by the licensed design professional and the building official. The materials supplier and concrete producers are responsible for performing testing and providing data on the expected performance of the products. If the proposed ASTM test methods and specifications pass, they will govern the data required by the supplier and producer. The performance and durability requirements of Chapter 19 of ACI 318-19 remain unchanged from previous versions of the code, but both durability and performance requirements may now be achieved in concrete mixtures using alternative cements. Materials specifications in ACI 318 are applicable for portland cement or blended cements, but are not necessarily applicable for alternative cements. For example, some alternative cements do not rely on a chemical reaction with water. Additionally, the maximum w/cm for alternative materials may be different than portland cement systems.

The concrete producer must provide evidence that the concrete containing alternative cements are constructable. They must consider mix proportions, compatibility with admixtures, mixing time, and restrictions on time in the mixer. The resulting mix must be placeable and behave consistently from batch to batch.

Conclusions

The concrete industry is proactively pushing forward with sustainability goals as seen from the General Services Administration's (GSA) Low Embodied Carbon Concrete Standards, PCA's Roadmap to Carbon Neutrality, ACI's sustainability initiatives. These goals will drive the concrete industry to use more SCMs, especially recycled materials or low-embodied carbon materials, to continue to build durable structures.

As changes to standards and availability of cementitious materials continue in the United States, changes to concrete specifications may be required to produce durable concrete. Materials that are available in abundance like landfilled bottom ash or fly ash have shown that they can offer the same durability against harsh environments as currently produced fly ash. Harvested fly ash is on the market now and Reclamation will likely have projects that source harvested ash if it is the only available option in the region. Technological advancements allow the landfilled material to be processed to meet ASTM C618 standards.

Cost savings could be found with several repair materials that offer rapid strength gain and high resistance to harsh chemical environments. Strengths can be used within hours rather than days. Many of these non- OPC repair materials are on the market now and could be used.

Ongoing research at Reclamation is important to keep up with changes in the industry. As more materials become commercially available and economically viable, Reclamation may consider their use in projects. For Reclamation to adopt, it is important that standard tests and specifications be developed and approved for consistency and more widespread use.

References

[1] ACI Committee E-701, "Cementitious Materials for Concrete," Farmington Hills, MI, American Concrete Institute, 2013.

[2] S. H. Kosmatka and M. L. Wilson, Design and Conctrol of Concrete Mixtures, 15th ed., Skokie, IL: Portland Cement Association, 2011.

[3] E. R. Dunstan, "Sulfate Resistance of Fly Ash Concretes - The R-Value," *ACI Special Publication SP100-103,* vol. 100, pp. 2027-2040, 1987.

[4] ASTM International, "ASTM C452-21, Standard Test Method for Potential Expansion of Portland-Cement Mortars Exposed to Sulfate," West Conshohocken, PA, 2021.

[5] ASTM International, "ASTM C1012, Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution," West Conshohocken, PA, 2018.

[6] "52.223-17 Affirmative Procurement of EPA-designated Items in Service and Construction Contracts," 2018. [Online]. Available: https://www.acquisition.gov/browse/index/far.

[7] ACI Committee 225, "Guide to the Selection and Use of Hydraulic Cements," in *ACI Collection*, Farminton Hills, MI, ACI International, 2015, pp. 28-30.

[8] ASTM International, "ASTM C150, Standard Specification for Portland Cement," West Conshohocken, PA, 2018.

[9] ASTM International, "ASTM C595, Standard specification for Blended Hydraulic Cements," West Conshohocken, PA, 2021.

[10] K. Bharadwaj, K. S. T. Chopperla, A. Choudhary, D. Glosser, R. M. Ghantous, G. D. Vasudevan, J. H. Ideker, O. B. Isgor, D. Trejo and W. J. Weiss, "Impact on the use of Portland-Limestone Cement on Concrete Performance on Plain or Reinforced Material," Oregon State University, Corvallis, OR, 2021.

[11] Portland Cement Association, "Roadmap to Carbon Neutrality," PCA, 2021.

[12] P. Tennis, M. Thomas and W. J. Weiss, "State-of-the-Art Report on Use of Limestone in Cements at Levels of up to 15%," Portland Cement Association, Skokie, IL, 2011.

[13] ASTM International, "ASTM C109-21, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens)," West Conshohocken, PA, 2021.

[14] ASTM International, "ASTM C157-17, Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," West Conshohocken, PA, 2017.

[15] D. R. Hooton, A. Ramezanianpour and U. Schutz, "Decreasing the clinker component in cementing materials: performance of Potland-Limestone Cements in concrete in combination with supplementary cementing materials," in *NRMCA Concrete Sustainability Conference*, Tempe, AZ, 2010.

[16] K. S. T. Chopperla, J. A. Smith and J. H. Ideker, "The efficacy of portland-limestone cements with supplementary cementitious materials to prevent alkali-silica reaction," *Cement,* vol. 8, 2022.

[17] S. Al-Shmaisani, R. Kalina, M. Rung, R. Ferron and M. Juenger, "Implementation of a Testing Protocol for Approving Alternative Supplementary Cementitious Materials: Natural Minerals and Reclaimed and Remediated Fly Ashes," 2018.

[18] R. Hooton and M. Thomas, "Sulfate Resistance of Mortar and Concrete Produced with Portland-Limestone Cement and Supplementary Cementing Materials: Recommendation for ASTM C595/AASHTO M 240," Portland Cement Association, Skokie, IL, 2016.

[19] ACI Committee 130, "ACI 130R-19, Report on the Role of Materials in Sustainable Concrete Construction," in *ACI Collection*, Farmington Hills, MI, ACI International, 2019, p. 40.

[20] P. C. Aitcin, Ed., Binders for Durable and Sustainable Concrete, 1st ed., New York, NY: Taylor and Francis Group, 2008.

[21] K. L. Scrivener, J. L. Cabiron and R. Letourneux, "Higher-Performance Concretes from Calcium Aluminate Cements," *Cement and Concrete Research,* vol. 29, no. 8, pp. 1215-1223, 1999.

[22] K. Scrivener, "Historical and present day applications of calcium aluminate cements," in *International Conference on Calcium Aluminate Cements*, 2001.

[23] J. H. Ideker, G. Gosselin and a. R. Barborak, "An Alternative Repair Materal: Basics and Practical Testing of Calcium Aluminate Cement Concrete," *Concrete International,* vol. 35, no. 4, pp. 33-37, 2013.

[24] R. Barborak, "Calcium Aluminum Cement Concrete (Class CAC Concrete)," TxDOT Special Specification SS-4491 Tip Sheet, 2010.

[25] M. Zajac, J. Skocek, F. Bullerjahn and M. B. Haha, "Effect of retarders on the early hydration of calcium-sulpho-aluminate (CSA) type cements," *Cement and Concrete Research,* vol. 84, pp. 62-75, 2016.

[26] K. Scrivener, "Calcium Aluminate Cements," in *Advanced Cement Technology*, Elsevier, 2003.

[27] M. G. Juenger, F. Winnefeld, J. L. Provis and a. J. H. Ideker, "Advances in Alternative Cementitious Binders," *Cement and Concrete Research,* vol. 41, no. 12, pp. 1232-1243, 2011.

[28] L. Burris, K. Kurtis and T. Morton, "Novel Cementitious Materials for Development of the Next Generation of Sustainable Transportation Infrastructure," FHWA-HRT-16-017, 2015.

[29] M. A. G. Aranda and A. G. D. l. Torre, "Sulfoaluminate Cement," in *Eco-Efficient Concrete*, Cambridge, UK, Woodhead Publishing Limited, 2013.

[30] A. Telesca, M. Marroccoli, M. L. Pace, M. Tomasulo, G. L. Valenti and P. J. M. Monteiro, "A hydration study of various calcium sulfoaluminate cements," *Cement and Concrete Composites ,* vol. 53, pp. 224-232, 2014.

[31] Buzzi Unicem USA, "CSA Cement by Buzzi Unicem USA," 2015. [Online]. Available: https://www.buzziunicemusa.com/documents/819248/843352/CSA+FAQ.pdf. [Accessed 12 May 2021].

[32] "RAPID SET CEMENT Datasheet," CTS, [Online]. Available: https://www.ctscement.com/datasheet/RAPID_SET_CEMENT_Datasheet_DS_012_EN?c=PRODUCTS&t=Professionals. [Accessed 4 May 2021].

[33] "Calumex Quick (CSA)," Caltra Nederland BV, [Online]. Available: https://caltra.com/product/calumex-quick/. [Accessed 4 May 2021].

[34] L. D. Glasser and N. Kataoka, "The chemistry of alkali-aggregate reaction," *Cement and Concrete Research,* vol. 11, no. 1, pp. 1-9, 1981.

[35] ASTM International, "Standard Specification for Rapid Hardening Hydraulic Cement," West Conshohocken, PA , 2019.

[36] ASTM International, "Standard Specification for Packaged, Dry, Rapid-Hardening Cementitious Materials for Concrete Repairs," West Conshohocken, PA, 2020.

[37] ASTM International, "ASTM C1157, Standard Performance Specification for Hydraulic Cement," West Conshohocken, PA, 2020.

[38] S. Sahu and R. Meininger, "Sustainability and Durability of Solidia Cement Concrete," *Concrete International,* vol. 42, no. 8, pp. 29-34, 2020.

[39] N. deCristofaro and S. Sahu, "CO2-Reducing Cement," *World Cement,* 2017.

[40] R. J. Thomas, H. Ye, A. Radlinska and S. Peethamparan, "Alkali-Activated Slag Cement Concrete," *Concrete International,* vol. 38, no. 1, pp. 33-38, 2016.

[41] M. A. Coelho, M. G. d. Silva, F. L. d. S. Souza, R. Sarmento, R. P. d. M. Frasson, S. M. d. M. Pinheiro, E. Zandonade and T. Morimoto, "Effects of Alkali-Activation of Slag Concrete," *ACI SP-229-28*.

[42] S. Al-Otaibi, C. J. Lynsdale and J. H. Sharp, "Performance of Alkali-Activated Slag Concrete," *ACI Special Publication SP202-29,* vol. 202, 2001.

[43] C. Cartwright, F. Rajabipour and A. Radlińska, "Shrinkage Characteristics of Alkali-Activated Slag Cements," *Journal of Materials in Civil Engineering,* vol. 27, no. 7, 2015.

[44] V. Bilek, M. Urbanova, J. Brus and D. Kolousek, "Alkali-Activated Slag Concrete—Development for Practical Use," *ACI Special Publication SP242-30,* vol. 242, 2007.

[45] ACI Innovation Task Group 10, "ACI ITG-10-R-18, Practitioner's Guide for Alternative Cements," 2018.

[46] A. Rodrigue, J. Duchesne, B. Fournier and B. Bissonnette, "Durability of Alkali-Activated Slag/Fly Ash Pastes and Concretes: an Overview of Performance Regarding Freezing and Thawing, Surface Scaling, Shrinkage and ASR," *ACI Special Publication SP 349-35,* vol. 349, pp. 508-521, 2021.

[47] ASTM International, "ASTM C618, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete," West Conshohocken, PA, 2019.

[48] ASTM International, "ASTM C989, Standard Specification for Slag Cement for Use in Concrete and Mortars," West Conshohocken, PA, 2018.

[49] M. C. G. Juenger, R. Snellings and S. A. Bernal, "Supplementary Cementitious Materials: New Sources, Characterization, and Performance Insights," *Cement and Concrete Research,* pp. 257-273, 2019.

[50] I. Diaz-Loya, M. Juenger, S. Seraj and R. Minkara, "Extending Supplelemtary Cementitious Material Resources: Reclaimed and Remediated Fly Ash and Natural Pozzolans," *Cement and Concrete Composites,* vol. 101, pp. 44-51, 2019.

[51] Charah Solutions, "Cost-Effective Ash Beneficiation Technology," Louisville, KY, 2021.

[52] S. L. Tritsch, L. Sutter and I. Diaz-Loya, "Use of Harvested Fly Ash in Highway Infrastructure," FHWA Tech Brief, 2021.

[53] E. Effinger, "Ash Harvesting and Technologies Critical to Boosting SCM Supply," *Ash at Work,* no. 2, pp. 14-20, 2021.

[54] ASTM International, "ASTM C1567, Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)," West Conshohocken, PA, 2013.

[55] G. Kaladharan, A. Gholizadeh-Vayghan and F. Rajabipour, "Review, Sampling, and Evaluation of Landfilled Fly Ash," *ACI Materials Journal,* vol. 112, no. 4, pp. 113-122, 2019.

[56] ASTM International, "ASTM C33, Standard Specification for Concrete Aggregates," West Conshohocken, PA, 2018.

[57] M. Cheriaf, J. C. Rocha and J. Péra, "Pozzolanic properties of pulverized coal combustion bottom ash," *Cement and Concrete Research,* vol. 29, no. 9, pp. 1387-1391, 1999.

[58] N. R. Arun, P. Singh and S. Gupta, "Utilisation of ground bottom ash in concrete," *Materials Today: Proceedings,* vol. 32, no. 4, pp. 663-669, 2020.

[59] C. Argiz, M. Á. Sanjuán and E. Menéndez, "Coal Bottom Ash for Portland Cement Production," *Advances in Materials Science and Engineering,* vol. 2017, p. 7, 2017.

[60] S. Oruji, N. A. Brake, R. K. Guduru, L. Nalluri, Ö. Günaydın-Şen, K. Kharel, S. Rabbanifar, S. Hosseini and E. Ingram, "Mitigation of ASR expansion in concrete using ultra-fine coal bottom ash," *Construction and Building Materials,* vol. 202, pp. 814-824, 2019.

[61] M. Kasaniya, M. D. A. Thomas and E. G.Moffatt, "Efficiency of natural pozzolans, ground glasses and coal bottom ashes in mitigating sulfate attack and alkali-silica reaction," *Cement and Concrete Research,* vol. 149, 2021.

[62] I. M. Milagre Martins, A. Gonçalves and J. C. Marques, "Durability and Strength Properties of Concrete Containing Coal Bottom Ash," in *International RILEM Conference on Material Science - AdIPoC - Additions Improving Properties of Concrete - Theme 3. International RILEM Conference on Material Science*, 2010.

[63] M.-H. Zhang and V. M. Malhotra, "High-Performance Concrete Incorporating Rice Husk Ash as a Supplementary Cementing Material," *ACI Materials Journal,* vol. 93, no. 6, pp. 629-636, 1996.

[64] W. Wilson and A. Tagnit-Hamou, "Workability and Hydration of Superplasticized Cementitious Mixtures with Rice Husk Ash," *ACI Materials Journal,* vol. 111, no. 5, pp. 491-500, 2014.

[65] N. P. Hasparyk, P. J. M. Monteiro and H. Carasek, "Effect of Silica Fume and Rice Husk Ash on Alkali-Silica," *ACI Materials Journal,* vol. 97, no. 4, pp. 486-492, 2000.

[66] P. K. Mehtra and K. J. Folliard, "Rice Husk Ash--a Unique Supplementary Cementing Material: Durability Aspects," *ACI Special Publication SP154-28,* vol. 154, pp. 531-542, 1995.

[67] IEA Bioenergy, "Options for increased use of ash from biomass combustion and co-firing," 2018.

[68] X. Wirth, D. Benkeser, N. N. N. Yeboah, C. R. Shearer, K. E. Kurtis and S. E. Burns, "Evaluation of Alternative Fly Ashes as Supplementary Cementitious Materials," *ACI Materials Journal,* vol. 116, no. 4, pp. 69-77, 2019.

[69] N. Ukrainczyk, N. Vrbos and E. A. B. Koenders, "Reuse of Woody Biomass Ash Waste in Cementitious Materials," *Chemical and Biochemical Engineering Quarterly,* vol. 30, no. 2, pp. 137-148, 2016.

[70] C. R. Shearer, "The Productive Reuse of Coal, Biomass, and Co-Fired Fly Ash," Dissertation, Georgia Institute of Technology, 2014.

[71] C. E. Pierce, H. Tripathi and T. W. Brown, "Cement Kiln Dust in Controlled Low Strength Material," *ACI Materials Journal,* vol. 100, no. 6, pp. 455-462, 2003.

[72] R. S. Ravindrarajah, "Usage of Cement Kiln Dust in Concrete," *The International Journal of Cement Composites and Lightweight Cocrete,* vol. 4, no. 2, 1982.

[73] F. F. Udoeyo and A. Hyee, "Strengths of Cement Kiln Dust Concrete," *Journal of Materials in Civil Engineering,* vol. 14, no. 6, 2002.

[74] P. Chaunsali and S. Peethamparan, "Novel Cementitious Binder Incorporating Cement Kiln Dust:," *ACI Materials Journal,* vol. 110, no. 3, pp. 297-304, 2013.

[75] M. Lachemi, K. M. Hossain, A. Lotfy, M. Shehata and M. Sahmaran, "CLSM Containing Cement Kiln Dust," *Concrete International,* vol. 31, no. 6, pp. 47-52, 2009.

[76] "Glass: Material-Specific Data," Environmental Protection Agency, 2021. [Online]. Available: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/glass-material-specific-data.

[77] ASTM International, "ASTM C1866-20, Standard Specification for Ground-Glass Pozzolan for Use in Concrete," West Conshohocken, PA, 2020.

[78] A. Zidol, "Optimization of the fineness of glass powder in binary cementitious systems," MSc. Thesis, Universite de Sherbrooke, 2009.

[79] A. Tagnit-Hamou and A. Bengougam, "The use of glass powder as supplementary cementitious material," *Concrete International,* vol. 34, no. 3, pp. 56-61, 2012.

[80] A. Hussein, A. Yahia and A. Tagnit-Hamou, "Statistical modeling of the effect of glass powder on concrete mechanical and transport properties," *ACI Materials Journal,* vol. 226, 2013.

[81] M. Christiansen and B. Dymond, "Effect of Composition on Performance of Ground Glass Pozzolan," *ACI Materials Journal,* vol. 116, no. 4, p. 10, 2019.

[82] A. Omran, N. Soliman, A. Zidol and A. Tagnit-Hamou, "Performance of Ground Glass Pozzolan as a Cementitious Material - A Review," *Advances in Civil Engineering Materials,* vol. 7, no. 1, p. 35, 2018.

[83] I. Fily-Pare, B. Fournier, J. Duchesne and A. T. Hamou, "Effects of Glass Powder on the Pore Solution of Cement Pastes," *ACI Special Publication SP-320,* vol. 320, 2017.

[84] G. Ke, W. Li, R. Li, Y. Li and G. Wang, "Mitigation Effect of Waste Glass Powders on Alkali Silica Reaction Expansion in Cementiitous Composite," *International Journal of Concrete Structures and Materials,* vol. 12, no. 67, 2018.

[85] ASTM International, "Standard Guide for Evaluation of Alternative Supplementary Cementitious Materials (ASCM) for Use in Concrete," West Conshohocken, PA, 2018.

[86] ASTM International, "Standard Guide for Harvesting Coal Combustion Products Stored in Active and Inactive Storage Areas for Beneficial Use," West Conshohocken, PA.

[87] ASTM International, "Standard Test Methods for Measuring the Reactivity of Supplementary Cementitious Materials by Isothermal Calorimetry and Bound Water Measurements," West Conshohocken, PA, 2020.

[88] ACI Committee 318, ACI 318-19, Building Code Requirements for Structural Concrete, Farminton Hills, MI: ACI International, 2019.