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INTEGRATING ALTERNATIVE SUPPLEMENTARY CEMENTITIOUS MATERIALS INTO NEXT GENERATION PAVING

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Introduction

Alternative supplementary cementitious materials (ASCMs) are entering the concrete industry, and over time these materials will provide specifiers options to address material supply challenges related to reductions in coal fly ash supplies and limited quantities of other supplementary cementitious materials (SCMs). In all industry roadmaps for carbon reduction across the concrete value chain, the primary near-term action is to reduce the clinker content in cement, and that requires increasing the amount of SCMs used in each concrete mixture. For example, in the United States, cements include less than 5% SCMs (PCA 2021). The Portland Cement Association (PCA) roadmap calls for increasing that number to 10% by 2030 and 20% by 2050 (PCA 2021). This will be achieved at the cement plant through the production of blended cements. However, SCM use at the point of concrete production is also expected to increase. The current use of SCMs at the ready mix plant varies geographically from approximately 10% to 20% of the total cementitious materials content (Athena 2020), but that number is also expected to increase in the near term. Under either scenario, SCM supply use must increase to meet industry goals.

Coal ash is the most commonly used SCM and is used for a variety of reasons. Historically, the primary form of coal ash has been fly ash, which was first used for cost reduction given that coal ash is a waste material and has typically been lower in cost than cement. The performance benefits of coal ash have also been known for almost 100 years (Davis et al. 1937), and the durability demands of modern concrete require the use of SCMs such as fly ash. However, there are challenges to the supply of fly ash given the conversion of coal-fired power plants to natural gas or discontinued operation of the plants altogether. One solution is a switch to harvested ash, which is coal ash originally placed in landfills or impoundments that is now being reclaimed, but increased use of these sources is hindered by the logistics of transporting these materials to markets and site permitting requirements for harvesting projects.

ASCMs offer several advantages that will fill gaps in SCM supply, and therefore it is important to begin to understand these materials. The purpose of this tech brief is to provide background information on ASCMs but to do so by placing them in the context of current SCMs and SCM specifications. It is important to view ASCMs as a continuation of SCM use, not a new direction, as the term “alternative” implies. As a note to the reader, this tech brief will discuss specific materials, but other ASCMs not discussed here are being developed and offer similar performance and availability.

Background

History of SCM Use

Hydraulic cement-based concrete is a mixture of mineral aggregate bound together by an inorganic cement that hardens through chemical reactions with water. This type of concrete is nearly as old as civilization itself (Wikipedia 2024a). Early hydraulic cement combinations comprised burnt lime and sand forming a mortar used to cement rocks together for structural purposes. Later advances used lime with naturally occurring reactive aluminosilicates to form concrete mixtures, the most well known being Roman concrete, which used volcanic ash sourced from Pozzuoli, Italy, known as "pozzolana" (Delatte 2001). Other pozzolana materials included Santorin earth and German trass (Wikipedia 2024b).

The cement used in modern concrete is portland cement, which has been in use now for 200 years. At first, portland cement was used primarily by itself as the cementing agent. Not long after its introduction, it was being blended with burnt lime, a source of calcium hydroxide, or other materials that were sources of reactive aluminosilicates. These latter materials are called "pozzolans" in recognition of their Roman predecessor. For example, Santorin earth was used in the construction of the Suez Canal from 1859 to 1869 (Mehta 1981), and the construction of the Los Angeles aqueduct between 1910 and 1912 used a finely ground pumice, a naturally occurring pozzolan, in a pozzolan-portland cement blend (ACI Committee 232 2012). It was the groundbreaking work of Davis et al. (1937), which showed the application of coal fly ash as a pozzolan, that led to the widespread use of this material today, where pozzolans and other SCMs are as necessary for hydraulic cement-based concrete as portland cement.

Each ingredient in a concrete mixture affects the mixture's performance, measured quantitatively by strength and various durability indicators such as permeability, resistivity, and air entrainment. Qualitatively, concrete is evaluated for properties such as pumpability, workability, and finishability, and of course cost is always a consideration. Today, concrete is evaluated by these measures but is also assessed for its global warming potential (GWP), measured in terms of carbon dioxide equivalents (CO_2 eq) (ACI Committee 323 2024). What we have learned over the last 100 years is that use of SCMs is one of the most effective tools to manipulate the properties of concrete to achieve many desired performance requirements.

What Is a Cement?

ASTM C125 Standard Terminology Relating to Concrete and Concrete Aggregates defines a hydraulic cement as "a cement that sets and hardens by chemical reaction with water and is capable of doing so under water." Portland cement comprises calcium silicate phases (i.e., dicalcium silicate [C_2S] and tricalcium silicate [C_3S]) that chemically react with water, forming a number of reaction products. The two key reaction products are calcium silicate hydrate (C-S-H) and calcium hydroxide ($Ca(OH)_2$, or CH). Note that ceramic notation is used to identify common oxides, where C = CaO, S = SiO_2, A = Al_2O_3, and H = H_2O. The simplified portland cement reaction with water is shown in equation 1.

$$(C_2S, C_3S) + H_2O \rightarrow \text{C-S-H} + Ca(OH)_2 \qquad (1)$$

The C-S-H product is desirable and is what provides the strength of a hardened portland cement. In contrast, CH is generally undesirable when considering strength and durability. Solid CH phases (portlandite) provide a minimal contribution to concrete strength, and CH is soluble in water, reaching its maximum solubility at the freezing point of water. Dissolution of CH increases a concrete's permeability, and dissolved hydroxide ions (OH^-) are a reactant in many concrete materials-related distress mechanisms. For these reasons, the reduction of CH is generally beneficial to concrete durability. However, dissolved hydroxide ions do affect the concrete porewater pH and create the conditions that cause passivation of embedded steel, eliminating the corrosion of reinforcing steel.

The most common hydraulic cement is portland cement meeting the requirements of AASHTO M 85 (ASTM C150) Standard Specification for Portland Cement. This material is well documented in other publications (Wilson and Tennis 2021). Other common hydraulic cements include those meeting the requirements of AASHTO M 240 (ASTM C595) Standard Specification for Blended Hydraulic Cements and ASTM C1157 Standard Performance Specification for Hydraulic Cement. Some SCMs comprise phases that are hydraulic.

What Is an SCM?

ASTM C125 defines an SCM as "[a]n inorganic material that contributes to the properties of a cementitious mixture through hydraulic or pozzolanic activity, or both." Pozzolans are not hydraulic cements but react in a manner that complements hydraulic cements. A pozzolan reacts with the CH produced by the hydraulic cement reaction, shown in equation 2 in its ionic form, to produce additional C-S-H, thereby increasing strength, reducing permeability, and minimizing the CH content. The simplified hydraulic and pozzolanic reactions are shown in equations 2 and 3.

$$(C_2S, C_3S) + H_2O \rightarrow \text{C-S-H} + Ca^{2+} + 2(OH^-) \qquad (2)$$

$$Ca^{2+} + 2(OH^-) + \text{pozzolan} + \text{water } (H_2O) \rightarrow \text{C-S-H} \qquad (3)$$

Because of this reaction with CH, pozzolans play a unique role in a concrete mixture and are generally sought for their ability to increase durability. The most common use is for mitigating alkali-silica reactivity (ASR). In the pozzolanic reaction, hydroxyl ions are removed from solution, eliminating a key reactant in the ASR reaction. Moreover, the formation of additional C-S-H reduces the cement paste's permeability, thereby limiting water flow through the cement paste and reducing access to another key reactant in the ASR reaction.

Hydraulic activity refers to a material's performance as a hydraulic cement in the manner described previously. Slag cement is the most common hydraulic SCM. It is termed a "latent" hydraulic cement, meaning that it reacts slowly when only in the presence of water. However, when blended with portland cement, the hydroxyl ions created by the cement's hydraulic reaction accelerate the slag reaction, creating C-S-H. The resulting C-S-H binds alkali metals, and the net result is a reduction in permeability through the formation of additional C-S-H and the binding of alkali hydroxides, which provides ASR mitigation. In short, slag cement provides the same benefits as a pozzolan.

Generally speaking, as the calcium content in an SCM decreases, the material becomes more pozzolanic and less hydraulic, assuming that it is an aluminosilicate-type material. The opposite trend holds as the calcium content increases. For this reason, types of coal ash are differentiated by their calcium content, where an ash classified as Class F comprises 18.0% CaO or less and an ash classified as Class C comprises more than 18% CaO. The other key component of an SCM is the amorphous silica (SiO_2) or alumina (Al_2O_3) or both. To form additional C-S-H, silica is required. When alumina is present, the reaction products may be C-S-H as well as calcium aluminate silicate hydrate (C-A-S-H) (Wang et al. 2024).

Requirements for Specifications and Tests

Properties Affecting an SCM's Performance in Concrete

The performance of SCMs has historically been associated with their classification within specifications. However, this linkage is not robust because approaches to classification have not directly measured performance, specifically reactivity. For the past 60 years, SCMs have been classified first by the source of the material and second by chemical prescription. The properties and characteristics evaluated have been specific to the type of SCM, not to SCMs in general. As one example, for most of its history, AASHTO M 295 (ASTM C618) Standard Specification for Coal Ash and Raw or Calcined Natural Pozzolan for Use in Concrete has used the sum of the oxides (i.e., the sum of $SiO_2+Al_2O_3+Fe_2O_3$) to classify fly ash. Recently in these specifications, limiting the CaO content has replaced limiting the sum of the oxides. However, the approach of using bulk composition continues today, in spite of research that has shown that numerous other factors impact fly ash reactivity, such as the glass phase content and composition (Hemmings and Berry 1987). In contrast, slag cement is specified using AASHTO M 302 (ASTM C989) Standard Specification for Slag Cement for Use in Concrete and Mortars, which uses no compositional limits to classify the material. Rather, classification is based on physical properties such as the slag activity index.

As ASCMs become more prevalent, and to increase the use of existing SCMs, a performance-oriented approach is necessary to measure fundamental material properties known to affect performance in concrete mixtures. The user community will need to develop experience using this approach, but it will provide a better indication of concrete performance than is provided by existing prescriptive specifications. In the following sections, key SCM properties are discussed, along with approaches to test for those properties.

Reactivity

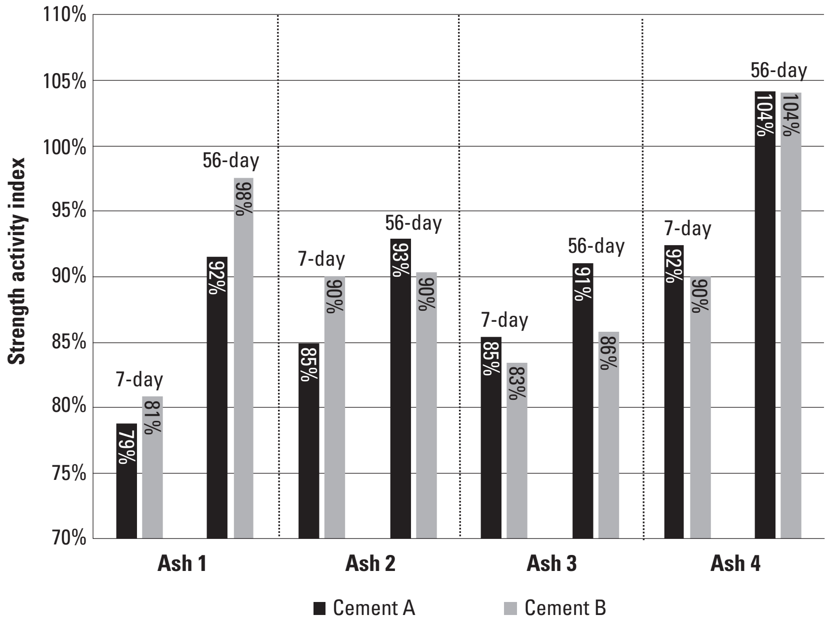
When selecting an SCM for use in concrete, a question commonly asked is how well the SCM performs relative to portland cement. After all, the material is being used to supplement or replace portland cement, so wanting to understand its relative performance makes perfect sense. The problem, however, is selecting which cement the SCM should be compared with. The specific job cement may not be available, and not all cements perform the same. The follow-on problem is that many other factors can impact the final concrete performance, making it difficult to isolate the contributions of the SCM in a concrete mixture.

A quantity of SCM will most likely not perform the same as an equal quantity of the cement being replaced. Ideally, the performance of an SCM compared to that of portland cement would be 1:1 or better. In reality, most SCMs do not provide the same strength development or permeability characteristics as portland cement in the same amount of time. That said, some provide comparable or improved characteristics at later ages (e.g., 28 days or beyond in some cases).

In current specifications, estimating the performance of an SCM relative to portland cement is addressed by means of a strength activity index (SAI) test. The SAI test takes different forms and has different limits depending on the material specification, but all variations of the test compare the strength of mortar specimens prepared using the test material to the strength of mortar specimens prepared using only portland cement. The resulting ratio of strengths is reported as a percent of the control sample. The most widely criticized variation is the SAI test used for coal ash and natural pozzolans. The test is detailed in ASTM C311 Standard Test Methods for Sampling and Testing Coal Ash or Natural Pozzolans for Use in Concrete and requires testing the SCM using a 20% replacement of cement in the test mortar mixture (i.e., 80% portland cement, 20% test material). The specification limits in ASTM C618 are a minimum SAI of 75% of control at 7 or 28 days, while in AASHTO M 295 the specification limits are a minimum SAI of 75% of control at 7, 28, or 56 days. A similar test is used in AASHTO M 302 (ASTM C989) for slag cement but is referred to as the slag activity test. This test differs from the procedure in ASTM C311 in that a 50% replacement of cement with slag is used in the test samples and the resulting strength ratio is used directly to classify the materials. The specification limit is based on the last five samples tested, with a Grade 80 slag having a minimum SAI of 75% of control, a Grade 100 slag having a minimum SAI of 95% of control, and a Grade 120 slag having a minimum SAI of 115% of control.

For fly ash, the SAI test has been criticized because its specification limits can be met by inert materials and because the test result varies based on the cement used in the test (Sutter et al. 2013). These shortcomings are illustrated in Figure 1, where four different Class F fly ash sources were tested using two different portland cements. Note that for slag cement, the SAI test is performed using a standard reference cement to eliminate variability in the test that is attributable to the cement.

The strength activity approach has merit as a “do no harm” test, but it does not provide an isolated, quantitative assessment of SCM performance. Recently, a set of tests was developed (Avet et al. 2016, Li et al. 2018) to measure SCM “reactivity,” which is a material property that indicates how well an SCM will perform in a concrete mixture. Reactivity is, in essence, a measurement of the degree or extent of the chemical reaction that occurs when an SCM is exposed to a solution that mimics a concrete porewater solution. The tests do not distinguish between hydraulic and pozzolanic reactions. The tests have been standardized as ASTM C1897 Standard Test Methods for Measuring the Reactivity of Supplementary Cementitious Materials by Isothermal Calorimetry and Bound Water Measurements and are also referred to as the rapid, reliable, and reproducible (R3) tests. Both tests involve exposing the SCM to a solution of calcium hydroxide, calcium carbonate, potassium sulfate, and potassium hydroxide and curing the mixture at 40°C [104°F] for 3 and 7 days.



Data from Sutter et al. 2013

Figure 1. Results from the strength activity index (SAI) test using four different sources of ASTM C618 Class F fly ash tested using two different portland cements

One of the two options in ASTM C1897 is then used to quantify the reactivity. Option A uses isothermal calorimetry to determine the cumulative heat release from the chemical reaction measured at 3 and 7 days, respectively. Option B determines gravimetrically the amount of water bound as a hydration product of the chemical reaction, referred to as bound water. Either can be used as a measure of the reactivity of an SCM. In the future, these new tests will be the basis of assessing the performance of ASCMs, as will be discussed later in this tech brief.

Fineness

Fineness is the term used to describe the particle size distribution of an SCM. For a cement or SCM, as the particle size decreases, the reactivity increases due to the increase in the specific surface area of the particles. Therefore, fineness is important to measure. The impact of fineness on reactivity is reflected in the SAI tests or the R3 tests. However, determining the fineness separately from the reactivity helps to isolate particle size effects from the effects attributable to the SCM's chemical or physical structure. The test currently used for fineness is described in ASTM C311 and involves determining the amount of material retained on a 325 mesh (45 micron) sieve (i.e., the amount of material coarser than 45 microns.) This approach provides one data point to describe the particle size distribution of an SCM, though it should be noted that two SCMs could have different particle size distributions while having the same fineness. Nonetheless, for a given source of SCM, the fineness test provides a simple quality assurance approach. Instrumentation-based methods are available for determining the actual particle size distribution, but these methods have not been standardized and therefore are not referenced in current material specifications.

Composition

The composition of an SCM is important but is difficult to limit in a specification. Specifically, as ASCMs emerge, a range of compositions will be seen. Some will mimic fly ash (i.e., aluminosilicate-based materials), while others may be calcium rich, possibly through the presence of calcium silicates or calcium carbonate. An ASCM may not be associated with specific precursor materials (e.g., coal or blast furnace slag), making current specific classifications not applicable. Therefore, as ASCMs are introduced, specifications will require the composition to be reported, but specification limits on composition will not be used.

Deleterious Components

The possible exception to the shift away from compositional limits will be for deleterious components. These will be measured in new specifications and, in some cases, limited. Three examples are loss on ignition (LOI), sulfate content, and chloride content. Determination of LOI has been part of cement and SCM specifications since the earliest days. For fly ash, LOI is synonymous with unburnt carbon included in the ash and has been limited by specifications because of its impact on air entrainment. The LOI of natural pozzolans has also been limited, but this practice has come under scrutiny recently. Natural pozzolans do not contain carbon and are not known to impact air entrainment, so the need to limit LOI in current specifications is unclear. More specifically, the LOI in natural pozzolans, as well as some ASCMs, could be hydrated minerals, and the degree to which these materials are deleterious is questionable. Even if the LOI fraction of an SCM is unburnt carbon, as is typically the case in coal ash, rejecting a material based on LOI alone does not make sense if the end use is not air-entrained concrete. Therefore, a report-only approach seems more practical, which is the approach to LOI being taken in new specifications. Sulfate content will continue to be limited in ASCM specifications, given the known concerns when materials with high sulfate contents are used in concrete. For sulfate content, there is precedent for allowing a material not meeting the specification limits to demonstrate performance using ASTM C1038 Standard Test Method for Expansion of Hydraulic Cementitious Material Mortar Bars Stored in Water. Chloride content will be reported but will likely not be limited in material specifications; it will need to be limited in concrete specifications, however, given that chloride can come from practically any ingredient in the concrete.

New Specifications for SCMs

As industry moves to increase the use of SCMs in concrete, and as ASCMs become available, it will be necessary to develop a new approach to specifying SCMs. Historically, SCM specifications have relied on prescriptive approaches that have not focused on material properties directly related to performance in concrete. Increasing the SCM replacement of portland cement beyond current levels will require better measures of SCM performance, requiring a shift away from broad classification approaches such as the use of bulk composition. In the case of adopting ASCMs, the challenge is that available standard specifications limit themselves by scope to cover SCMs that result from specific processes or raw material sources. The numerous emerging ASCMs simply do not align with these limitations. Further, even if these scope limitations were removed, the acceptance testing and specification limits prescribed may not adequately characterize these new materials.

An additional challenge with ASCMs is the nascent state of the industry growing around these materials. Numerous ASCMs are emerging, and the task of developing individual, focused specifications for each material would be daunting; in reality, it would be impossible. In addition to the ASCMs already scaling up to production levels, other new technologies are being developed and will be entering the market. In short, future developments will likely result in more ASCMs, and writing a prescriptive specification for each is not realistic. The only practical approach is to develop a performance-oriented specification that does not limit materials based on source or production processes. In the end, all SCMs, emerging or existing, will be used in concrete, and the specifier will require the same performance from an SCM for a given application, regardless of the source. A high-level summary of the key expectations is presented in Table 1, along with the properties to measure and report as part of a standard specification.

Currently at ASTM, the performance-oriented specification for SCMs being developed will measure and report, and in some cases provide limits for, the material properties outlined in Table 1. Note that this new specification is intended for use with any SCM, but the underlying intention is to serve as a specification for ASCMs. Existing materials will continue to use their respective prescriptive specifications in the near term, although evolution in those specifications is needed and will continue. The proposed new specification will address the properties summarized in Table 1, as well as deleterious components such as sulfate content, chloride content, and LOI and other necessary parameters such as water requirement and limits on uniformity. In the new specification, many tests for material properties will not have limits, but mandatory measurement and reporting will be required.

The key specification limits will address reactivity and SAI, and a material must qualify by meeting the limits for both tests. The specification is still being balloted and discussed within ASTM, but for these two measurements the philosophy is as follows. The SAI test will be more stringent compared to the version used in AASHTO M 295 (ASTM C618). The current proposal is to raise the SAI specification limit from 75 to 80 and require the SCM to qualify either at 7 and 28 days or at 56 days. For the reactivity test, much discussion has focused on setting the limits given the wide range of reactivities that occur among all SCM types. The subcommittee tasked with this effort based its proposal on research conducted by RILEM (Londono-Zuluaga et al. 2022) that provides minimum limits to distinguish reactive materials (i.e., SCMs) from nonreactive materials (i.e., inert fillers). The trade-off is between setting a low limit, and risking acceptance of an inert filler as an SCM, or setting a high limit, and risking rejection of slowly reacting or less reactive SCMs that may, in fact, have excellent properties at later ages. The latter characteristic has been demonstrated throughout history, with examples such as those previously discussed in this tech brief (e.g., Roman concrete). The current proposal is to require an SCM to qualify by testing for reactivity in accordance with ASTM C1897, using the bound water approach (ASTM C1897 Method B). The proposed minimum requirement for bound water is 3.6 g H_2O/100 g SCM. Meeting this limit provides a 66% probability that the SCM is as reactive as a moderately reactive coal fly ash (Londono-Zuluaga et al. 2022).

This new performance-oriented specification is nearing completion, and other changes in specifications are in progress. Recently, ASTM acted to create a new natural pozzolan specification, ASTM C1945. In its inaugural form, its requirements will be identical to those of AASHTO M 295 (ASTM C618) Class N. However, it is planned to evolve the specification to include new classes or types to better group and specify similar materials (e.g., raw natural pozzolans, calcined natural pozzolans, manufactured pozzolans) and to integrate new testing requirements such as ASTM C1897. Other specification developments include broadening ASTM C1697 Standard Specification for Blended Supplementary Cementitious Materials to include ground glass pozzolan (GGP). Another change is to include limestone as a blending component, thereby supporting blends of limestone and calcined clay (LC2) that can be blended with portland cement at the ready mix plant to produce limestone, calcined clay, and clinker (LC3) cements.

Table 1. Performance expectations of SCMs for use in concrete, the SCM properties that impact that performance outcome, and standard tests for measuring those properties

Performance Expectation	Material Property Measured	Standard Test Method
Improve strength development	Reactivity, strength activity, fineness	ASTM C1897
Reduce concrete permeability	Reactivity, fineness	ASTM C1897
Mitigate ASR	Reactivity, fineness, expansion	ASTM C1897, ASTM C1567
Improve sulfate resistance	Reactivity, fineness, expansion	ASTM C1897, ASTM C311, ASTM C1012
Achieve air entrainment	Foam index, uniformity	ASTM C1827, ASTM C311

The evolution of specifications will continue as agencies, suppliers, and practitioners move away from prescriptive specifications that address a select group of materials toward performance-oriented specifications that support the use of a wide range of SCMs, both existing SCMs and emerging ASCMs.

Materials Used as SCMs or ASCMs

SCM versus ASCM. What's the Difference?

The term alternative supplementary cementitious material or ASCM has become integrated into the language of construction materials through a progressive series of actions starting as early as 20 years ago, recognizing that these materials would be emerging. Efforts to take the next step and integrate these materials into construction specifications, however, have only recently gained momentum. As new materials have been proposed over the last 10 to 15 years, the existing specification environment caused each new SCM to try and force its way under an existing specification, an impossible task given the scope limitations of each specification. The phrase "this material is just like fly ash" was common, and still is. The other common claim is, "This material meets all the requirements of AASHTO M 295," which is true only if one ignores the title and scope of AASHTO M 295 (ASTM C618), which limits the specification to coal ash and natural pozzolans.

The solution to this issue of identity became more confused in 2011 with the publication of ASTM C1709 Standard Guide for Evaluation of Alternative Supplementary Cementitious Materials (ASCM) for Use in Concrete. This specification introduced and defined alternative supplementary cementitious materials as "inorganic materials that react pozzolanically or hydraulically, and beneficially contribute to the strength, durability, workability, or other characteristics of concrete, and do not meet Specifications C618, C989/C989M, C1240, and C1866/C1866M." (Note that ASTM C1866/1866M was recently added after that specification was introduced in 2020.) Though this definition is correct, ASTM C1709 instructs the reader to test the material for compliance with one of the cited specifications, implying acceptance of the process of fitting each ASCM into an existing specification even though doing so is impossible without changes to the existing specification. This definition of an ASCM has been adopted by industry, but corresponding modifications of existing specifications have not been made to allow ASCMs under existing specifications once their equivalency has been proven. The previously introduced performance-oriented specification under discussion at ASTM is intended to meet the growing need to provide a specification environment for these emerging materials.

The wide range of ASCMs, in terms of source, composition, and physical properties, is not unique. It can be argued that existing SCMs have a similarly broad range of attributes and that existing SCMs are evolving as well. A confounding part of the influx of new SCMs is that all of these new materials are entering the market at the same time, leading to an immediate, steep learning curve for the specifier. For this reason, it is important that all SCMs are measured by the same tests and that similar or equivalent properties are expected when an SCM is used in a specific application. However, to better understand the seemingly vast array of ASCMs, there is value in developing a taxonomy to bring some order to the apparently wide arrange of choices. The taxa should be grouped into types having similar processes of origin, similar compositions, or both. Through this classification process, order can be applied to what seems to be an uncontrolled proliferation of new materials. Ultimately, the goal should be to discuss all of these materials in terms of SCMs, with no distinction made for alternative SCMs because all SCMs are alternatives to each other.

The following classification is suggested here but has not been formally adopted by any standards-writing organization. In the remaining sections, each group is discussed, and examples of available materials are presented where information is available.

1. Natural SCMs
    a. Raw Natural Pozzolans
    b. Calcined Natural Pozzolans
2. Byproduct-Based SCMs
    a. Coal Ash
    b. Slag Cement
    c. Ground Glass Pozzolan
    d. Silica Fume
3. Processed SCMs
    a. Pyro-processed SCMs
    b. Mechanically Processed SCMs
    c. Chemically Processed SCMs
    d. Mechanochemically Processed SCMs
    e. Blended
4. Manufactured SCMs
    a. Pyro-processed SCMs
    b. Mechanically Processed SCMs
    c. Chemically Processed SCMs
    d. Mechanochemically Processed SCMs
    e. Biologically Processed SCMs
    f. Blended SCMs

Natural SCMs

Natural Pozzolans

As introduced earlier in this tech brief, natural pozzolans have been used in construction dating back to the Roman era. More recently, the use of natural pozzolans in concrete has increased, due in part to the need for alternatives to coal ash as well as their proven performance record. Natural pozzolans are currently specified under AASHTO M 295 (ASTM C618) Class N, but ASTM recently adopted a new standalone natural pozzolan specification, ASTM C1945 Standard Specification for Raw or Calcined Natural Pozzolan for Use in Concrete. Currently, ASTM C1945 is identical to AASHTO M 295 (ASTM C618) Class N. However, changes to this new standard are planned with the intent of adding new criteria, tests, and limits to better distinguish the performance of natural pozzolans in concrete. Natural pozzolans either are used raw (i.e., as mined, with minimal processing such as drying and sizing) or are calcined.

Raw Natural Pozzolans

The most common types of raw pozzolans used without calcination are volcanic minerals such as pumaceous materials (e.g., pumice, pumicite), obsidian, and rhyolitic materials. These materials have a high amorphous content as a result of their geological process of formation (i.e., rapidly cooled lava flows). These materials generally require a minimum level of processing that may include grinding and sizing to achieve the necessary fineness. Diatomaceous earth (DE) is another natural pozzolan used in a raw form. Given their physical characteristics, diatom frustules, the silica-rich skeletons of diatoms found in DE, are porous and function to hold moisture (Wikipedia 2024c). Therefore, DEs used as SCMs may increase water demand (Abrão et al. 2020). These natural pozzolans, however, tend to be more reactive than pumaceous materials (Kasaniya et al. 2021).

Calcined Natural Pozzolans

Calcining is a unit operation that converts a portion of a solid material into a gas to remove that portion permanently from the solid material (Wikipedia 2024d). The most familiar application of calcining is in the production of portland cement, where limestone (calcium carbonate [$CaCO_3$]) is heated to release carbon dioxide (CO_2), leaving a solid residue of calcium oxide (CaO). This process requires a significant input of heat (i.e., ~900°C [1,650°F]). In comparison, the calcining temperature range for natural pozzolans is lower, typically 550°C to 850°C [1,025°F to 1,565°F]. Calcining raw natural pozzolans releases water that is bound as part of the mineral structure and thereby allows the silica and alumina components to rearrange, leading to an increased amorphous phase content, which increases the reactivity of the pozzolan. Raw natural pozzolans are sometimes calcined, but the use of pozzolans in their raw form is more common. A common use of calcination, and one that is increasingly becoming a focus of industry, is the calcination of clay minerals to form a pozzolan. This process is discussed below under the section on manufactured SCMs.

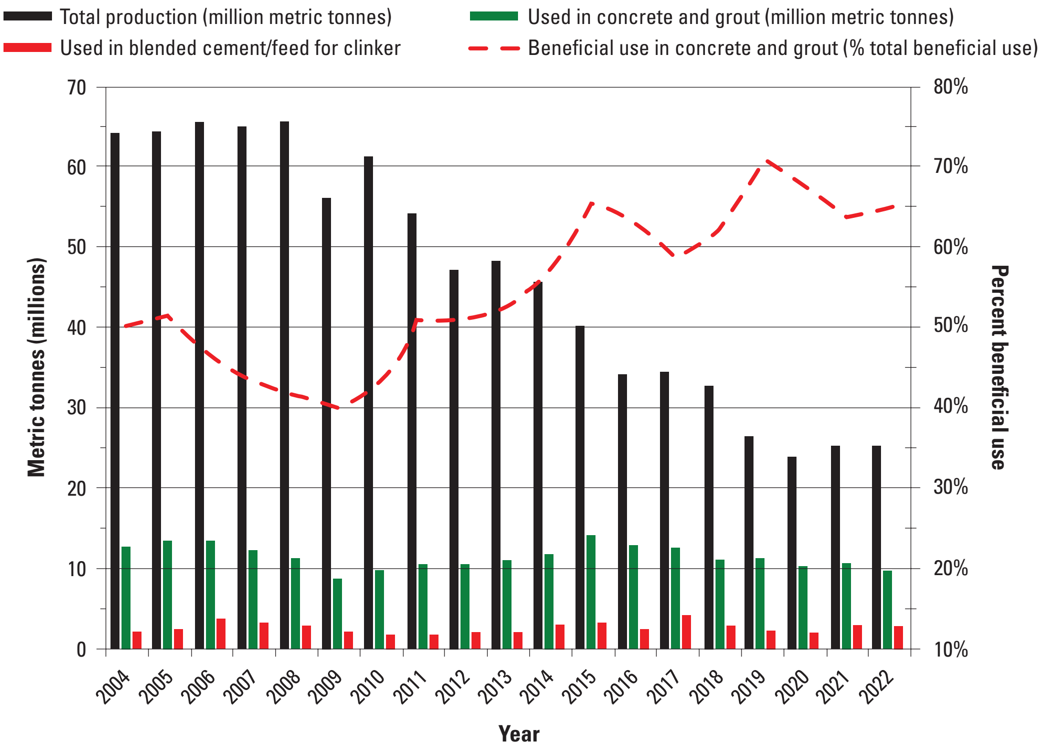
Byproduct-Based SCMs

Industrial byproducts having pozzolanic or hydraulic properties have been the predominant type of SCMs used for the past 50 years. The following are the current materials of this type that have a national standard specification.

Coal Ash

The first ASTM specification for coal fly ash was published in 1954, titled ASTM C350 Fly Ash for Use as Admixtures in Portland Cement Concrete. For comparison, the first ASTM specification for natural pozzolans was published in 1958, titled ASTM C402 Raw or Calcined Natural Pozzolans for Use as an Admixture in Portland Cement Concrete. Though natural pozzolans were being used as many as 75 years before the groundbreaking work of Davis et al. (1937) documented the benefits of using fly ash in concrete, the early interest in coal fly ash was likely due to the ready supply and low cost of fly ash at the time, which readily made it the SCM of choice.

As shown in Figure 2, coal fly ash production reached its maximum in 2008, with just over 65 million metric tonnes (72 million short tons) reported. Production in 2022 was reported to be approximately 25 million metric tonnes (28 million short tons). This reduction is one of the main drivers of demand for new SCMs in many markets. Beneficial use in concrete and grout, as a percentage of total beneficial use, was approximately 65% in 2022. Note that over the time period shown in Figure 2, the absolute tonnage of ash used has remained relatively constant year to year; an increase in the use of fly ash has not occurred, while the amount of concrete produced has undoubtedly increased.



Data from ACAA n.d.

Figure 2. Coal fly ash production and use, 2004–2022

In 2023, ASTM C618 was changed from covering coal fly ash to covering coal ash, which has been defined to include bottom ash as well as fly ash. Additionally, the specification was changed to allow for processing to meet the specification. This change enables the production of harvested ash, which is covered in the section on processed SCMs below. In 2024, the American Association of State Highway and Transportation Officials (AASHTO) adopted the same changes in AASHTO M 295. Bottom ash is currently being provided in some markets, typically blended with fly ash. As an example, Eco Materials is providing blends of fly ash and bottom ash from a number of sources in Texas, and the materials have been approved by the Texas Department of Transportation (TxDOT). Eco Materials is also projected to provide bottom ash and fly ash blends from the Coal Creek, North Dakota, facility, in the second quarter of 2026.

Slag Cement

The use of slag cement can be traced back to the 1700s, but modern use increased with the commissioning of the first granulator at Sparrows Point, Maryland, in 1982 (ASTM International 2006) and the publication of ASTM C989 Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars, also in 1982. The AASHTO counterpart, AASHTO M 302, was first published in 1986. Note that the title and terminology for ASTM C989 was changed from “Ground Granulated Blast-Furnace Slag” to “Slag Cement” in 2009. According to the United States Geological Survey (USGS), the amount of granulated slag shipped in the United States in 2021, the most recent year for which data are available, was estimated to be 3.0 metric tonnes (3.3 million short tons), and approximately 99.8% of the granulated slag was used as a cementitious material in concrete (USGS 202).

Slag cement supplies are expected to remain relatively constant out to 2030. The worldwide trend is for electric arc furnace steel production to increase, production by blast furnace/basic oxygen furnace to decrease, but overall production to increase and offset the reduction in blast furnace use (Lempriere 2024). Slag imports are expected to be a significant part of the total US slag cement supply chain as steel production shifts to Asia and India. Slag cement imports in 2023 were 23% higher than in 2022 (USGS 2024). Another factor in the limited domestic supply is the shortage of granulators in the United States. However, in 2024 Heidelberg Materials announced a new slag cement processing facility in Texas, providing an additional capacity of approximately 450,000 metric tonnes (500,000 short tons).

Ground Glass Pozzolan

In 2018, the most recent year for which data are available from the Environmental Protection Agency (EPA), 11.2 million metric tons (12.3 million short tons) of container glass were produced, which is the largest single source of recycled glass. Of this supply, 2.8 million metric tons (3.1 million short tons) were recycled, and only a small fraction of this made its way into concrete given the lack of material recovery facilities (MRFs) that separate glass and the even smaller number of GGP producers. The estimated annual production of GGP is on the order of 35,000 metric tonnes (40,000 short tons), but additional capacity is planned, primarily in the eastern United States. In 2020, ASTM published ASTM C1866 Standard Specification for Ground-Glass Pozzolan for Use in Concrete. The standard establishes two glass types: Type GS is basic container glass and Type GE is for e-glass, an industrial byproduct that is not widely available. Type GS is the predominate type of GGP. ASTM Committee C09 currently plans to include GGP meeting ASTM C1866 as a blending component in ASTM C1697 for blended SCMs. The ASTM C1866 specification for GGP will be included in the 2025 edition of ACI 318.

Silica Fume

Silica fume is a byproduct of the production of ferrosilicon or silicon metal in an electric arc furnace. As the name implies, it is captured from the exhaust gas of the furnace through a condensation process. Silica fume has a very high amorphous content and a particle size on the order of 0.1 to 0.2 micrometers (ACI Committee 234 2006). For comparison, this is 10 to 100 times finer than a fine coal fly ash. There are other forms of silica, such as fumed silica, precipitated silica, and gel silica, but these are not equivalent to silica fume (ACI Committee 234 2006). Their use in concrete should be thoroughly vetted through trial batching and trial field placements before use. Colloidal silica is yet another form of silica and is 1 to 2 orders of magnitude finer than silica fume in terms of particle size.

The first known use of silica fume in concrete is presented in U.S. Patent 2,410,954 (Sharp 1946). Silica fume is used where high strength, very low permeability, or both is required. A common use is in concrete bridge decks. The widespread use of silica fume is hindered by cost and supply. Silica fume is specified under AASHTO M 307 (ASTM C1240) Standard Specification for Silica Fume Used in Cementitious Mixtures.

Processed SCMs

Processed SCMs are byproduct-based SCMs that are either processed to meet the applicable specification or processed to add properties that exceed the minimum requirements of the applicable specification. In both cases, the processed SCM, in its final form, complies with the applicable specification. The only specifications for byproduct-based SCMs that explicitly permit processing are AASHTO M 240 (ASTM C618) for natural pozzolans and coal ash, ASTM C1945 for natural pozzolans, and ASTM C1697 for blended SCMs. AASHTO M 302 (ASTM C989) for slag cement implicitly allows for the use of processing additions by stating that the maximum amount used shall comply with the requirements of AASHTO M 327 (ASTM C465) Standard Specification for Processing Additions for Use in the Manufacture of Hydraulic Cements. Processing is required for most, if not all, coal ash harvesting operations. The types of processing that occur vary with the material and the performance requirements. General groupings of processes are provided below with examples.

Pyro-processed SCMs

Pyro-processing involves heating the SCM to temperatures in excess of that required for drying. The most common application of pyro-processing is to remove unburnt carbon from coal ash to meet LOI requirements. This is commonly referred to as carbon burnout. A number of approaches to pyro-processing have been used, and as harvested ash becomes more common, other methodologies will be developed. One approach used is the SEFA Staged Turbulent Air Reactor (STAR)™ technology, which uses a proprietary process to accomplish carbon removal. The reactor can also affect size distribution and, in some cases, serve to remove mercury or other contaminants (Fedorka et al. 2013). The technology has been deployed at multiple harvesting locations, including three retired Duke Energy coal-fired power stations in North Carolina (Norton 2020).

Mechanically Processed SCMs

Mechanical processing includes operations such as grinding or sizing. Both may be required for harvested coal ash operations, but any processing is used only when necessary, given the increased energy and capital costs. Grinding is the costliest processing operation and is therefore used only when other approaches such as sizing will not accomplish the needed beneficiation. The most likely application of grinding in the near-term will be for processing some bottom ash sources. Bottom ash, in general, is coarser than fly ash and less amorphous, both characteristics resulting in reduced reactivity compared to fly ash from the same source. As particle size decreases, reactivity increases (Poudel et al. 2024). As previously noted, Eco Materials is projected to provide bottom ash and fly ash blends from the Coal Creek, North Dakota, facility in the second quarter of 2026. The bottom ash fraction will be ground to ensure compliance with AASHTO M 295 (ASTM C618).

Sizing is used along with grinding to minimize overgrinding, and in some cases sizing by itself can produce an SCM of adequate fineness. The coarse oversize material can be removed and used for other applications. In some cases, sizing is used to produce an ultrafine SCM that far exceeds the fineness requirements of AASHTO M 295 (ASTM C618) and has a higher reactivity than the unprocessed material. Recognizing this possibility, AASHTO M 321 Standard Specification for High-Reactivity Pozzolans for Use in Hydraulic-Cement Concrete, Mortar, and Grout was developed to specify this type of SCM. This specification applies to pozzolanic materials and differs from AASHTO M 295 (ASTM C618) in a number of ways. First, while it still relies on the sum of the oxides to specify chemical requirements (i.e., the sum of SiO_2+Al_2O_3+Fe_2O_3), the specification limit is increased. In previous versions of AASHTO M 295 (ASTM C618), the sum of the oxides was limited to 70.0% minimum for Class F ash and 50.0% minimum for Class C ash. A higher sum of the oxides indirectly means a lower calcium content (Sutter et al. 2013). In AASHTO M 321, however, the sum of the oxides is limited to 75% minimum. The other major difference is the fineness requirement, which is 34% in AASHTO M 295 (ASTM C618) but limited to 10% in AASHTO M 321, hence the role of sizing for the latter. Another difference in AASHTO M 321 is the testing regime used, which is based on AASHTO M 307 (ASTM C1240) for silica fume. This standard likely cannot be met without sizing or grinding the SCM.

Chemically Processed SCMs

Chemical processing is primarily used to treat unburnt carbon to minimize air-entraining agent (AEA) adsorption without resorting to the energy-intensive processes associated with physically removing the carbon. However, it is likely that other chemical processes may be developed in the future to accomplish other goals, such as carbon sequestration. An example of a product to mitigate AEA adsorption is RestoreAir® by Eco Materials, which is a chemical used to pretreat coal ash to reduce the adsorption capacity of the carbon and effectively neutralize the carbon with respect to AEA adsorption. The technology has been used for freshly produced ash but will become increasingly important as the use of harvested ash increases. In many cases, the reason coal ash was placed in landfills and impoundments originally was because of its high LOI. Therefore, much of the harvested ash will need processing to be useable in air-entrained concrete, and chemical processing will be one approach employed.

Mechanochemically Processed SCMs

The processing of SCMs often entails a combination of mechanical and chemical processing operations. When these unit operations are performed simultaneously, the approach is referred to as mechanochemical processing. One example of a product created using this approach is PozzoSlag®, an SCM produced by Eco Materials. The process involves mechanically mixing an SCM, typically in a ball mill, with a small quantity of proprietary additives. The result is a significant increase in the reactivity of the SCM. In its Texas facility, for example, Eco Materials starts with an AASHTO M 295 (ASTM C618) Class C precursor material and produces a final product that not only meets the strength activity index requirements of AASHTO M 295 (ASTM C618) but also meets the more demanding slag activity index requirements of AASHTO M 302 (ASTM C989). Eco Materials is applying the same PozzoSlag® technology to natural pozzolans. In 2026, the company will commission a natural pozzolan source in Oregon, producing an estimated 225,000 metric tonnes per year (250,000 short tons per year) of performance-enhanced natural pozzolans.

Another emerging technology based on the mechanochemical approach has been developed by Carbon Upcycling of Calgary, Canada. This technology uses a modified ball mill that is sealed and injected with carbon dioxide (CO_2) during the grinding process. The process results in particle size reduction and the carbonation of any free calcium in the precursor material. However, the carbonation process results in a demonstrable increase in reactivity beyond that expected from size reduction alone. Precursor materials used to date include coal ash, natural pozzolans, blast furnace slag, steel slag, calcined clay, ground glass, and various mineral processing waste materials. The company markets the process as mechanically assisted chemical exfoliation (MACE). The technology has not yet been used in full-scale production, but the company did successfully participate in a demonstration project conducted by the Minnesota Department of Transportation (MnDOT) at MnROAD (Weitzel et al. 2024). The company is also working with Ash Grove Cement to integrate the process into the latter's Mississauga, Ontario, cement plant. This installation will use CO_2 captured from the cement operations to carbonate a locally sourced byproduct-based SCM.

Blended SCMs

Blended SCMs will become a larger part of the total SCM market as ternary blends become more common. A blend offers the obvious advantage of utilizing silo space at the ready mix plant more efficiently but has the disadvantage of reduced flexibility in mixture designs. However, particularly for small ready mix operations or on-site mixing for paving operations, blends offer simplicity and consistency. The ASTM C1697 specification permits blending of any of the byproduct-based SCMs except for GGP. However, ASTM C1866-compliant GGP will soon be added to the blending specification. Under ASTM C1697, a blend is classified by the largest-quantity component. For example if a blend is 70% natural pozzolan and 30% coal ash, the blend would be classified as a Type N blend, and the material must meet all requirements of ASTM C618 Class N as well as any additional requirements of ASTM C1697.

Future developments for ASTM C1697 center on integrating ground calcium carbonate into the specification. ASTM C1797 Standard Specification for Ground Calcium Carbonate and Aggregate Mineral Fillers for Use in Hydraulic Cement Concrete provides a material specification to support the addition of ground limestone to the blending specification. The driving force for this addition is to support the introduction of so-called LC2 blends (i.e., limestone and calcined clay). As discussed in the section below on manufactured SCMs, LC3 is arguably the fastest growing new technology. The LC3 blends are produced at a cement plant but can also be produced at a ready mix plant by providing an LC2 blended SCM to the ready mix producer, which in turn is combined with portland cement to produce LC3.

Manufactured SCMs

As discussed throughout this tech brief, the existing SCM supply faces challenges, particularly due to the reduction in coal fly ash production but also due to an increase in demand. Additionally, industry has persistently called for more uniformity in SCM properties. The combination of these forces has led to the development of materials specifically manufactured for use as SCMs, all of which are considered ASCMs. Manufactured SCMs are produced using a precursor material that is not an SCM.

Manufactured SCMs offer some advantages. First, the production facility can be located near the point of use or near a means of low-cost transportation to a market, such as a navigable waterway or rail line. However, this advantage may be offset by transportation restrictions on any necessary precursor materials. Another advantage is that for manufactured materials, quality control can be more readily implemented to provide more uniformity in performance. Consider that a key factor causing specifiers to limit coal ash use is inconsistency in the product; coal fly ash is a waste product, and its characteristics change as the operation of the power plant changes. Manufactured SCMs, in contrast, can potentially be more consistent and allow for larger, consistent substitution levels in concrete mixtures. An additional advantage of manufactured SCMs is that additional properties, such as carbon sequestration, can be included as part of the manufacturing process.

The disadvantage of these materials is the fact they are new and therefore give rise to questions of long-term performance (i.e., durability). Moreover, given the history of tying SCM specifications to particular sources of materials (e.g., coal ash, blast furnace slag), manufactured SCMs do not fall under existing specifications. To address this latter issue, a performance-oriented specification is under development at ASTM whose scope will cover both these alternative SCMs and existing SCMs.

The following sections discuss various types of manufactured SCMs grouped by their means of production.

Pyro-processed SCMs

As is the case with processed SCMs, pyro-processing for manufactured SCMs involves heating the precursor material to temperatures in excess of that required for drying. The most well-known SCM produced by pyro-processing is calcined clay. Clay materials, in their natural state, are not SCMs. However, the calcining process can be used to dehydrate the clay mineral structure and allow the silica and alumina components to rearrange and form an amorphous aluminosilicate that is reactive and can be used as an SCM. Kaolinite clay is the preferred source given its composition ($Al_4Si_4O_{10}(OH)_8$), and for years high-purity kaolinite has been used in ceramics production. When kaolinite is calcined at approximately 700°C to 850°C (1,300°F to 1,550°F), metakaolin is formed ($Al_2Si_2O_7$), which by itself has been used as an SCM but has not been widely adopted. Recently, lower grade kaolinite (e.g., clay materials with less than 50% kaolinite) has been used to produce calcined clay for LC3 (Scrivener et al. 2018). The production of LC3 is expected to grow significantly in the next 5 to 10 years as the industry seeks ways to reduce the use of portland cement.

Calcined clay has been considered by some as a natural pozzolan, but it generally does not meet the requirements of AASHTO M 295 (ASTM C618) Class N, typically because it does not meet the water requirement. As the new natural pozzolan specification (ASTM C1945) evolves, calcined clay will be included, likely through the addition of a classification for manufactured SCMs. Until that change occurs, calcined clay will be specified under the new performance-oriented SCM specification that is also under development at ASTM. As previously discussed in this tech brief, the inclusion of calcined clay and limestone blends under the existing blended SCM specification (ASTM C1697) is being discussed at ASTM. This change would support the production of LC2 and facilitate the production of LC3 blends at the point of concrete production.

Another pyro-processed SCM under development is OPUS SCM™, produced by the Colorado-based company Terra CO2. The material has very similar chemical and physical properties to coal fly ash. Whereas coal fly ash comes from the volatilization of inorganic minerals in coal, and the subsequent solidification of those minerals in the exhaust stream of a power plant, the Terra CO2 process starts with a silicate mineral feedstock (i.e., sands and gravels) and subjects it to a similar partial melting and solidification. This process results in carbon reduction advantages due to several factors. First, the processing plant is designed to be small and serve local markets, meaning that the ASCM can be produced near the market, which minimizes transportation impacts. Second, coal is not used, either as a fuel or as a feedstock, eliminating a major source of CO_2 generation. Further, the process is designed to work with industrial renewable energy sources that, once available, can move the production process towards carbon neutrality. Last, as previously mentioned, a manufactured product offers more opportunity for quality control at the point of production and potentially a more consistent product, which in turn supports the concrete industry's goal of increased SCM replacement levels.

Mechanically Processed SCMs

Currently, no manufactured SCMs produced using mechanical processes are known to be in production. However, much research is being directed towards mechanical activation of various waste materials, including steel slag (Snelling et al. 2023) and mine tailings (Martins et al. 2021). Mechanical activation has also been shown to be effective as a means of activating clay as an alternative to the use of pyro-processes (Tole et al. 2019).

Mechanical activation essentially involves grinding to produce a very fine material, increasing the specific surface area and thereby increasing the reactivity of a marginally reactive material. In most cases, size reduction by itself is not enough to induce reactivity, but through the comminution process, internal strain is created in the mineral structure, which may make the mineral reactive if it has a suitable composition (i.e., rich in silica and alumina).

Chemically Processed SCMs

One intent of using chemical processes is to move away from the use of limestone as a precursor to avoid the process-related emission of CO_2 resulting from the conversion of calcium carbonate to calcium oxide. Chemical processes may also result in lower energy requirements compared to mechanical processes or pyro-processes. Some chemically processed manufactured SCMs are moving into pilot-scale production and are receiving significant financial support from both the private and public sectors.

One emerging company in this field is Brimstone. The company has patented a novel process that uses calcium-rich silicate rocks (e.g., basalt) as the precursor material to coproduce portland cement and an SCM in the same process. The calcium-rich silicate rocks are milled and leached for calcium and other elements, and those rocks are then refined and used in raw meal for clinker production, essentially eliminating the calcination process from portland cement production. The remaining leached rock is recovered as an amorphous silica-rich residue and processed into an SCM. Brimstone will be scaling its process at a technical demonstration plant in Reno, Nevada, in the coming years and will follow with a commercial demonstration plant that is partially supported by a grant from the U.S. Department of Energy Office of Clean Energy Demonstrations.

Another startup company, Fortera, has already moved to the pilot plant stage with the commissioning of a manufacturing facility with a capacity of 13,500 metric tonnes (15,000 tons) per year that is co-located at the CalPortland cement plant in Redding, California. The Fortera ASCM is a deviation from what is normally considered an SCM. It is pure calcium carbonate formed from waste CO_2 captured from cement kilns or other industrial sources. The Fortera process creates a reactive calcium carbonate product that the company markets as ReAct™ Blend. Calcium carbonate occurs in nature in three different mineral forms: calcite, vaterite, and aragonite.

Each has the same chemical composition (i.e., $CaCO_3$) but a different crystal structure. Calcite is the most stable form under normal atmospheric conditions. Vaterite is the form produced as ReAct™, and when exposed to water it converts to calcite. The transition from vaterite to calcite comes with a change in particle shape from a rounded, equiaxed particle to a rod-like structure. The calcite rods intermix with the hydration products formed from portland cement and serve to strengthen and densify the resulting hardened cement paste. Carbon reduction occurs by embedding the calcite in the cement paste and reducing the portland cement content due to the strength imparted by the SCM. Because the process uses waste CO_2, a ReAct™ facility can be sited with a cement plant, allowing the ReAct™ Blend to be used as part of a blended cement product or delivered as a standalone SCM.

Mechanochemically Processed SCMs

Like with processed SCMs, combined mechanical and chemical processes are being explored for the production of manufactured SCMs. As an example, the previously discussed process developed by Carbon Upcycling is being tested with various nonreactive mineral precursor materials. Steel slag is another material that researchers are examining for use as an SCM, and mechanochemical processes are among the beneficiation approaches being evaluated (Snellings et al. 2023).

Biologically Processed SCMs

Biological processes are also being evaluated for the production of manufactured SCMs. Prometheus Materials has a patent-pending process that combines algae with natural sources of calcium. The algae use CO_2 from the atmosphere to carbonate the material, which in turn can be used as an SCM in concrete products. The material has not yet been distributed commercially but has been used in demonstration projects, including concrete and concrete block production.

Blended SCMs

As previously discussed, the blending of SCMs such as calcined clay with limestone will most certainly feature in SCM production in the near future. Blending SCMs with specialized non-SCM materials is also being done commercially. One commercially available product is produced by Carbon Limit, which has developed CaptureCrete™, a blend of natural pozzolans and a metal oxide catalyst. The combined material increases adsorption of CO_2 from the atmosphere, increasing both carbonation depth and the amount of carbon captured through carbonation of the portland cement paste. This carbon is permanently sequestered in concrete in the form of calcium carbonate.

Closing

The role of SCMs in the concrete industry has never been more important than it is today. Durable concrete requires SCMs, and efforts to reduce portland cement use are increasing the demand for SCMs of all types. New SCMs are beginning to enter the concrete construction industry, and, as they do, specifications need to evolve to permit their use. For better or worse, the transportation construction industry is where these new materials will be tested first, which presents both the challenge of adopting new technologies and the opportunity to lead a transformation in concrete construction. The next generation of concrete paving will provide opportunities for agencies, suppliers, and practitioners to gain experience with these new materials, and, with time, what was once an alternative will become business as usual.

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About the National Concrete Pavement Technology Center

The mission of the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University is to unite key transportation stakeholders around the central goal of developing and implementing innovative technology and best practices for sustainable concrete pavement construction and maintenance.