Concrete Task Group

WORK PRODUCT FINAL REPORT

Supplementary Cementitious Material Supply Look-Ahead

July 2021

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Contents

Purpose

This report continues and expands upon the content in the 2016 report, *Fly Ash Current and Future Supply*. Each report was compiled in response to fly ash supply shortages in California and represent a joint effort sponsored by the Caltrans Concrete Task Group in the Pavement and Materials Partnering Committee (formerly Rock Products Committee) and comprised of industry and Caltrans members. The details of the supply shortages are recorded along with current and future supply outlook of Supplementary Cementitious Materials (SCMs) used in Caltrans projects. The state of SCM use, testing, and acceptance used by other states and in national standards were compared. Several mitigation strategies are discussed. This report strives to serve as justification for future actions to improve Caltrans' ability to respond to supply shortages. The compiled information about mitigation strategies and industry knowledge about the potential of such strategies will also serve as guidance for future Caltrans efforts to adapt to a changing energy market.

Background on use of SCMs in Caltrans projects

A 1985 field investigation of the Simi Valley Freeway found the alkali-silica reaction (ASR) to be causing deterioration. After more structures across the state were found to have the same ASR issue, active projects began requiring 15% replacement of portland cement by fly ash to address ASR. In the years following the initial introduction, research performed at Caltrans Transportation Laboratory led specification developers to increase the fly ash requirement to 25% cement replacement which has been included in specifications since 1997. The 2010 Caltrans Standard Specifications changed supplementary cementitious materials (SCM) requirements to address the environmental impact of concrete usage. The 2010 Caltrans Standard Specifications removed the minimum portland cement content and maximum limits on SCMs allowing for reductions in total portland cement used and consequently reductions in the CO_2 released.

Performance characteristics of SCMs are recorded in the Caltrans Concrete Technology Manual as guidance for use of SCMs in concrete construction. Since the publication of the manual, technological development and new practices necessitate an update to the performance characteristics of many of the SCMs.

Currently Caltrans specifies SCM content to meet one of the following requirements.

1. *Any combination of portland cement and at least 1 SCM, satisfying equations 1 and 2.*

   Equations 1:

   $[(25 \times UF)+(12 \times FA)+(10 \times FB)+(6 \times SL)]/MC \geq X$

   UF = silica fume, metakaolin, or UFFA, including the quantity in blended cement, lb/cu yd

   FA = natural pozzolan or fly ash complying with AASHTO M 295, Class F or N, with CaO content up to 10 percent, including the quantity in blended cement, lb/cu yd

   FB = natural pozzolan or fly ash complying with AASHTO M 295, Class F or N, with CaO content greater than 10 percent and up to 15 percent, including the quantity in blended cement, lb/cu yd

   SL = GGBFS, including the quantity in blended cement, lb/cu yd

   MC = minimum quantity of cementitious material specified, lb/cu yd

   X = 1.8 for innocuous aggregate, 3.0 for all other aggregate

   Equation 2:

   $MC - MSCM - PC \geq 0$

   Where:

   MC = minimum quantity of cementitious material specified, lb/cu yd

   MSCM = minimum sum of SCMs that satisfied equation 1, lb/cu yd

   PC = quantity of portland cement, including the quantity in blended cement, lb/cu yd

2. *15 percent Class F fly ash with at least 48 oz of $LiNO_3$ solution added per 100 lb of portland cement. The CaO content of the fly ash must not exceed 15 percent.*

Requirement 1 is specified to ensure a minimum amount of SCMs for ASR mitigation, whereas requirement 2 is specified to reduce CO_2 release from use of additional portland cement.

Requirements are specified for concrete in freeze-thaw areas controlling the amount of SCMs with the following equation.

The cementitious material must satisfy the following equation:

[(41 x UF)+(19 x F)+(11 x SL)]/TC ≤ 7.0

Further, in areas where deicing chemicals will be used, SCMs are controlled by the following equations.

The cementitious material must be composed of any combination of portland cement and at least 1 SCM satisfying the following equation:

Equation 1:

[(25 x UF)+(12 x FA)+(10 x FB)+(6 x SL)]/TC ≥ X

The SCM must satisfy the following equations:

Equation 2:
4 x (FA + FB)/TC ≤ 1.0

Equation 3:
(10 x UF)/TC ≤ 1.0

Equation 4:
2 x (UF + FA + FB + SL)/TC ≤1.0

The concrete mix design must satisfy the following equation:

Equation 5:
27 x (TC – MC)/MC ≤ 5.0

As a result of these specification, Caltrans projects use hundreds of thousands of short tons of SCMs per year.

Overview of the Historical Cases of Fly Ash Shortage (Including Recent Shortages) in California

In 2016, a nation-wide fly ash shortage occurred. Several factors combined to reduce the amount of coal burned, including warm weather during winter months, plant maintenance prior to summer, and shutdown of coal burning power plants due to lower prices of natural gas and higher than usual hydroelectric yield.

Following the 2016 fly ash shortage, the AASHTO Subcommittee on Materials (SOM) published a report which included surveys of each state on local fly ash supply issues. Of the 52 respondents, 42 had experienced supply issues within the previous four years. The surveyed agencies also indicated which class of fly ash experienced shortage issues. Solely Class F fly ash supply issues were found by 22 states, Class C fly ash supply issues were reported by 8 states, and 12 states reported supply issues of both types (FHWA Subcommittee on Materials, 2016).

The 2016 AASHTO SOM study indicates that, along with the national shortages, regional shortages occur regularly and can affect states differently. California, located relatively far from many domestic fly ash sources, is in a more precarious position in the event of a shortage, due to shipping costs. One such regional shortage for California occurred in late 2020.

In September 2020 Caltrans learned of two events affecting the fly ash supply of two primary suppliers to California.

The contract between fly ash distributor Boral and the Bridger Power Plant located in Wyoming had been discontinued. By October, Boral no longer had access to the supply from the Bridger Power Plant. The new distributor chose to supply to a different region, leaving California with lower supply.

The other major supplier to California, Salt River Materials Group, lost significant supply from its largest producer, Four Corners Power Plant. Four Corners Power Plant chose to use their entire fly ash supply internally for a reclamation project. The result of this loss was a reduction of capacity from 30k tons to 10k tons per month supplied to California for a minimum of three months.

To date, the sudden reduction in supply resulted in over 40 Caltrans projects reporting impact to one or more mix designs. Most projects affected did not experience a significant delay to the schedule but spent increased resources to acquire and approve alternatives.

State of Use

In recent years, fly ash has represented the majority of SCM use on Caltrans project mix designs. Fly ash represents around 90% of the pozzolan use for concrete production in California (Sunrise Resources). During the 2020 fly ash shortage, contractors were faced with choosing an alternative way to proceed. Although slag was the most chosen alternative, some contractors chose Natural Pozzolans, alternative sources of fly ash, or 100% portland cement (PC). A breakdown of alternatives chosen by impacted project and contractor can be seen in Figure 1. This data only includes projects where the concrete production schedule or the whole project schedule were impacted by the fly ash shortage. In this data set, proposals for 100% PC include only projects where SCM was required; only in limited cases were these 100% PC proposals accepted by Caltrans. Many more projects used a fly ash alternative during the shortage but did not report impacts or delay due to suppliers having already switched to an alternative.

Availability of any SCM may change as a result of specification changes or industry adapting to increased demand of SCM alternatives to fly ash. To ensure Caltrans is not negatively impacted by future shortages, this report focuses on available information related to future SCM demand, current production capacity, and potential future capacity.

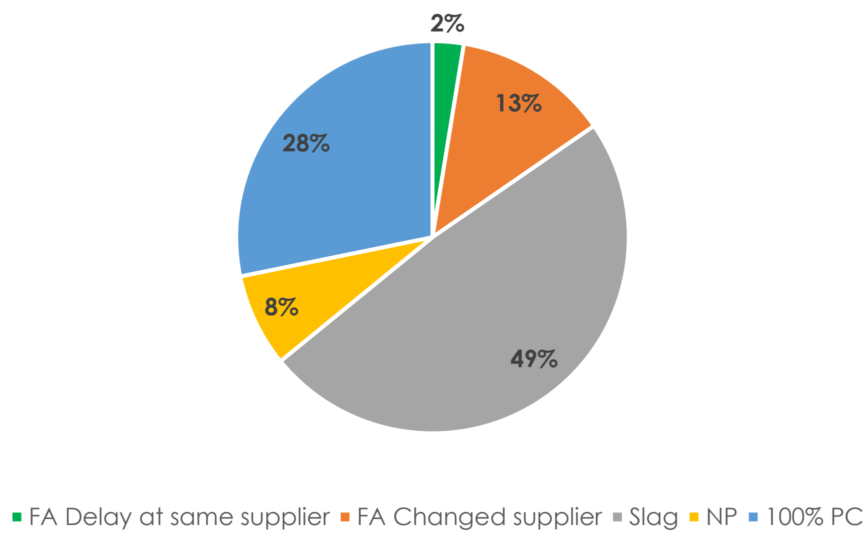

Figure 1- Alternatives requested during 2020 fly ash shortage by project and contractor

Critical review of SCM production and consumption rates across the country

Fly Ash

Background

Fly ash, known as the most widely used SCM in concrete, is the by-product of burning finely ground coal fuel mixtures in electric power generation plants. During combustion, the coal's mineral impurities, including clay, feldspar, quartz, and shale fuse in suspension and are carried away from the combustion chamber by exhaust gases. In the process, the fused material cools and solidifies into glassy particles called fly ash. The fly ash is then collected from exhaust gases using bag filters or electrostatic precipitators as a finely divided powder (Kosmatka and Wilson 2016).

The potential for using fly ash as an SCM in concrete has been known since the early 1900s (Anon 1914). However, the fly ash from power generation plants did not become widely available until the 1930s (ACI 232, 2004). Since then, the use of fly ash has increased, with over 85% of the fly ash consumed in 2019 being used as a replacement for portland cement or to produce blended cements (ACAA 2019).

Used in conjunction with portland cement, fly ash contributes to the properties of concrete through hydraulic or pozzolanic activity (or both). The ash provides substantial improvements in engineering properties and reductions in cost and carbon footprint of concrete. The availability of high-quality fly ash sources across the country have made fly ash the most widely used SCM. Today, fly ash is used in over 50% of ready-mix concrete mixtures (Kosmatka & Wilson 2016). Highway construction and concrete production has become highly dependent on a steady supply of quality fly ash to support durability and to meet other current performance expectations.

The availability of fly ash is a concern to Caltrans, since it is the most common SCM used in concrete to meet Caltrans specifications. Caltrans specifications call for the use of SCMs to both mitigate alkali silica reactivity (ASR) in concrete and for lower greenhouse gas (GHG) intensive concrete mixes. The requirement to use fly ash or other SCMs for ASR mitigation dates to 1998. It has typically required a minimum fly ash amount of 25%, unless the aggregate source can be proved innocuous, in which case only 15% SCM/fly ash is required. In addition, Caltrans amended its specifications in 2010 to allow for less energy intensive concrete mixes by removing the minimum requirements for the amount of cement, removing maximum limits on the amount of fly ash and other SCMs, and allowing the blending of up to 3 cement/SCM materials in concrete mixes. The result is that Caltrans projects consume about one-third of the fly ash used in California, or about 375,000 tons of the roughly 1-million-tons of fly ash used in California annually.

The readily available supply of adequate quality ash with suitably consistent characteristics is no longer available to agencies in some markets. Many states are citing current shortages of fly ash or are anticipating shortages. In a survey of 40 states performed by Armaghani and Cavalline (2020), 13 states reported current shortages in the availability of fly ash (Alabama, Florida, Illinois, Maine, Massachusetts, Michigan, Missouri, New Jersey, New York, North Dakota, Oregon, Rhode Island, and Texas), 16 other states (Arizona, Arkansas, Colorado, Connecticut, Delaware, Georgia, Idaho, Minnesota, Mississippi, Montana, Nebraska, North Carolina, South Dakota, Tennessee, Vermont, and Washington) predicted future shortages, and the remaining 11 did not report any shortages. Switching to other SCMs, including slag cement is reported to be one of the main solutions in these states (Armaghani and Cavalline 2020).

Trends in Generation and Usage of Fly Ash in U.S.

For the decades between 1960 and 2000 the utilization of fly ash and other coal combustion products (CCPs) have increased due to several factors, including various rulings by the Environmental Protection Agency and the development of industry standards and specifications requiring their use in construction products. Since the early 2000s, the volume of fly ash produced has declined, as shown in the data released by the American Coal Ash Association (ACAA 2019). Based on the data presented in Figure 2, over 29 million tons of fly ash was produced in 2019, indicating about 60% reduction in comparison to the 2005 production data. The consumption rates were also reduced during this period, exhibiting a reduction from 29 million tons in 2005 to 17 million tons in 2019.

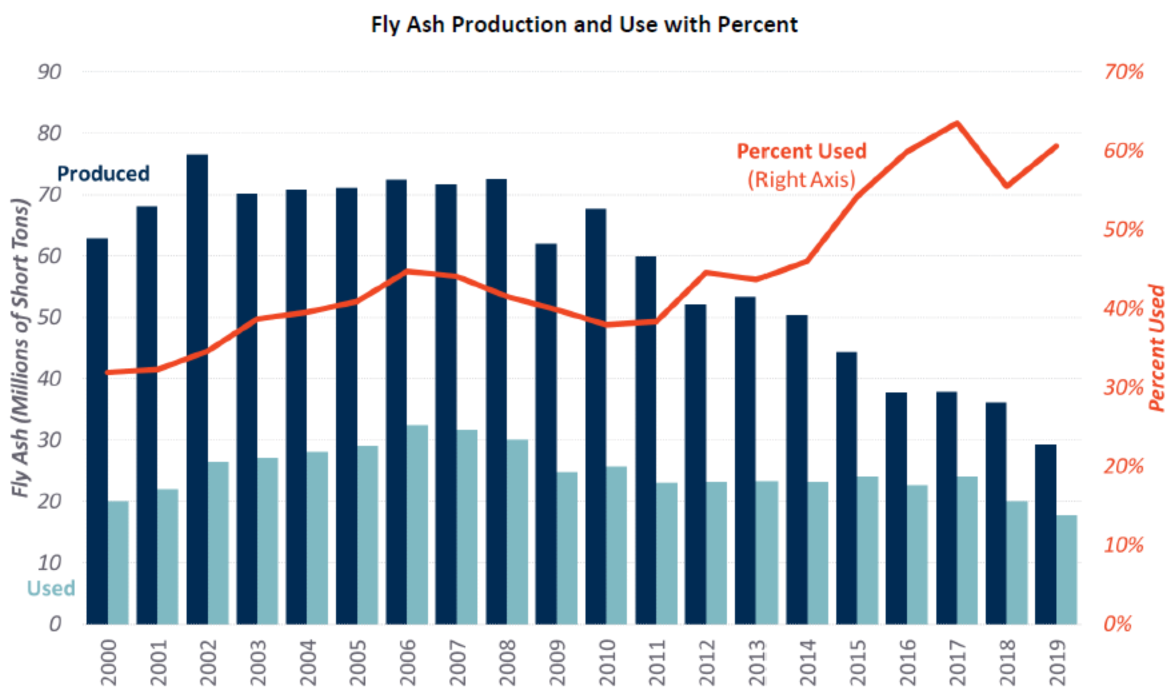

Figure 2- Fly ash production and usage data provided by American Coal Ash Association

Changes in air quality control measures to meet environmental regulations have impacted the chemical composition of the ash, as well as some physical properties, making the ash less ideal for use in concrete. The emission control technologies installed at power plants to comply with mercury, sulfur and other

2011 emission standards by the Environmental Protection Agency (EPA) impacted the availability of fly ash for use in concrete. Mercury emission restrictions on cement plants, enacted in 2015, may have also reduced the demand for fly ash as a raw material in clinker manufacturing.

The increase in use of natural gas and other energy sources, as well as seasonal changes in the demand for energy from coal-fired power plants is also resulting in long-term reduction in fly ash availability along with variability in both supply and characteristics.

With the reduction in demand for coal as the fuel source for electric energy generation, the reality that energy is the product, and fly ash is the byproduct of the power industry, is becoming clear to many stakeholders. The U.S. Energy Information Administration (EIA) is expecting a long-term increase in growth rate for U.S. electricity demand as shown in Figure 3. However, the majority of the expected growth is relying on sources other than coal as shown in Figure 4.

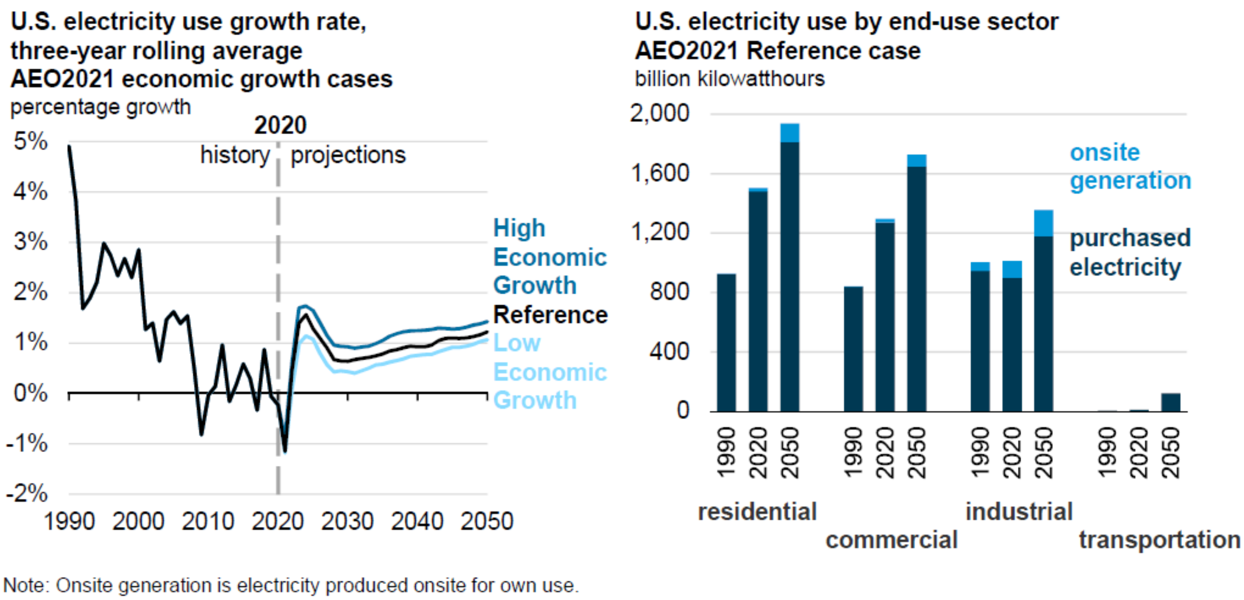

Figure 3- U.S. electricity demand data provided by U.S. Energy Information Administration

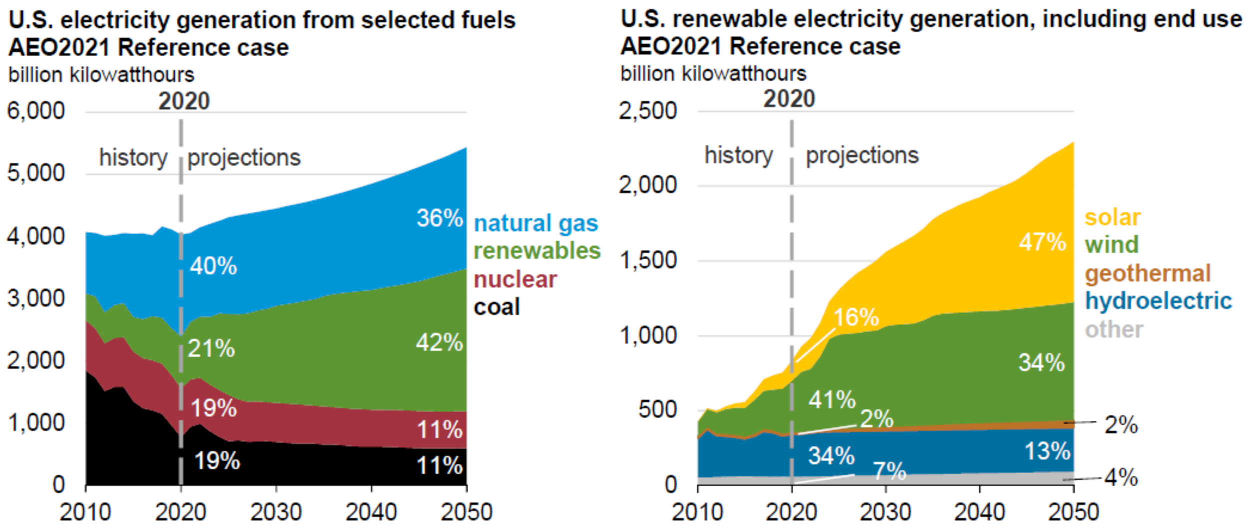

Figure 4- U.S. electricity generation data for different sources provided by U.S. Energy Information Administration

The EIA also projects potential short-term increases in coal production and consumption in U.S., followed by a steady reduction for the next few decades as shown in Figure 5.

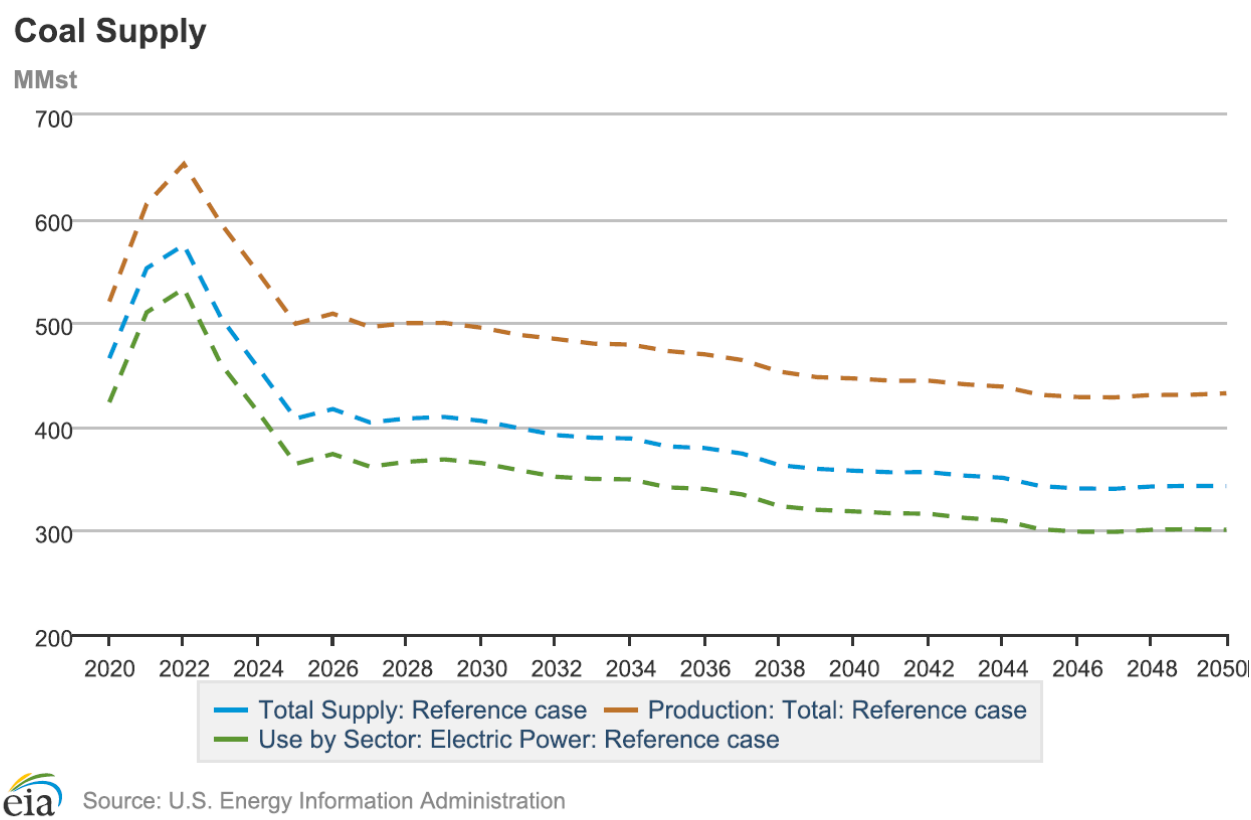

Figure 5- U.S. coal supply data and estimated consumption rates in electric power generation plants provided by U.S. Energy Information Administration

Further detailed estimates on coal production in different geographic locations, shown in Figure 6, indicates more uniform and steady production for Appalachian and interior regions of the U.S., and major reduction in coal production in western parts of the country. Based on the results presented in this figure, it is expected for the coal production in western areas of the U.S. to drop from 355.7 million tons in 2021 to 275 million tons in 2026.

The EIA estimations also project significant reductions in coal-based electric power generation during the next five years, due to the plant retirements as shown in Figure 7.

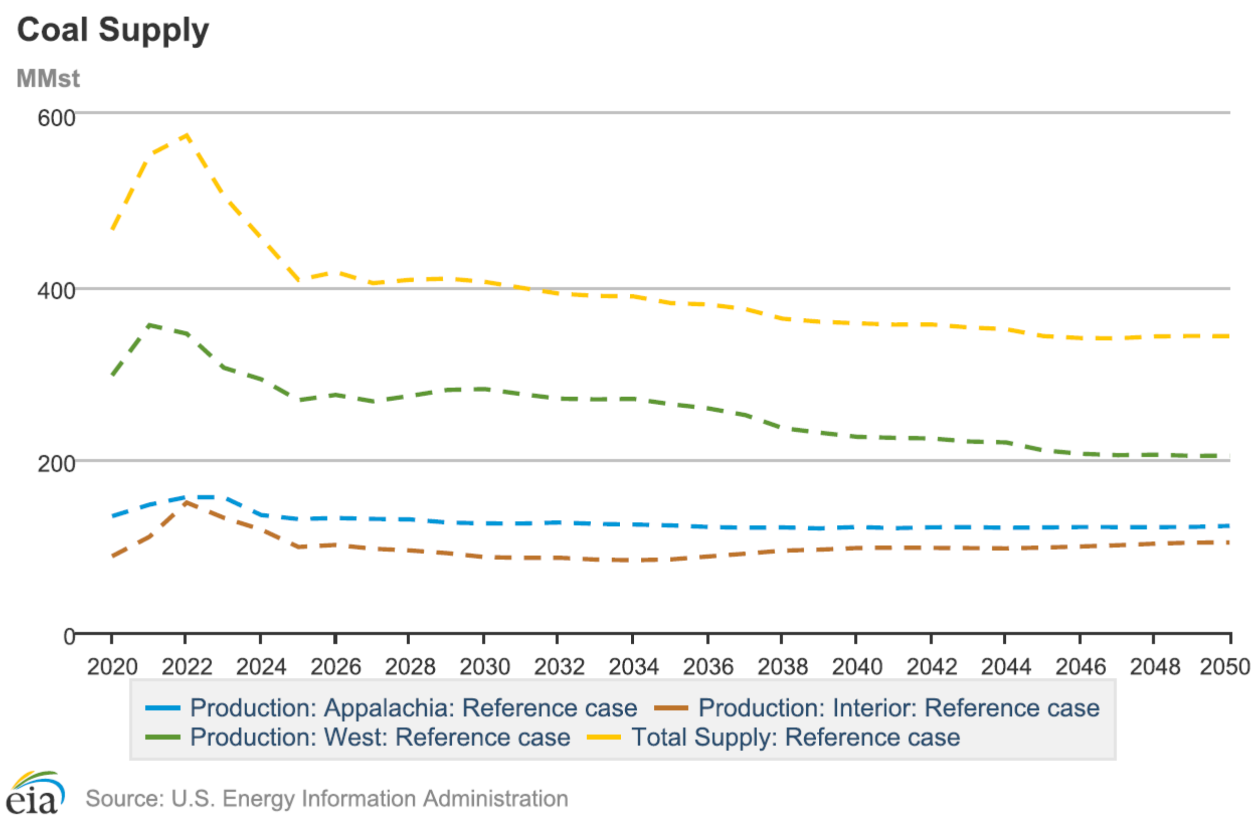

Figure 6- U.S. coal supply data at different areas of the country provided by U.S. Energy Information Administration

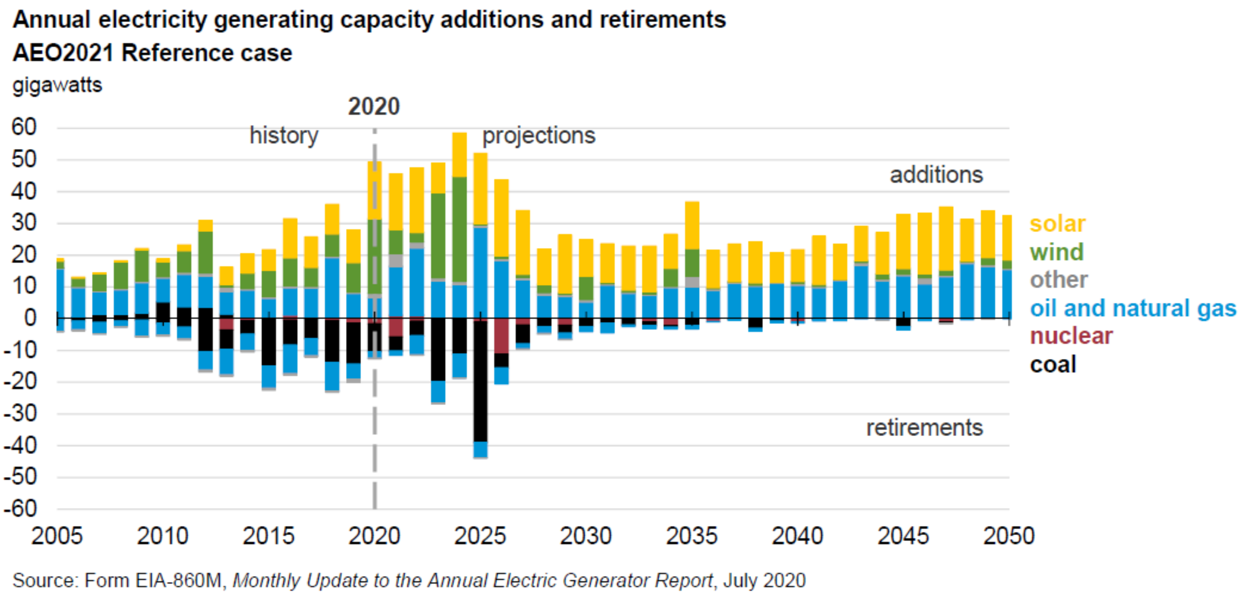

Figure 7- U.S. coal supply data at different areas of the country provided by U.S. Energy Information Administration

5-Year Outlook of the Availability and Usage of Fly Ash in California

The below estimates are provided by the industry members of the committee regarding the availability and consumption of fly ash in California and neighboring states for the next 5 years.

- Sellable fly ash **production** for AZ, NM, CO, UT, ID, WY, and NV at about 9.2 M tons over the next 5 years (1.84M TPY)
    - Approximately 150K tons *produced* in CA (Trona) over the same 5-year period (30K TPY)
- Fly ash **Usage** (as an SCM) for AZ, NM, CO, UT, ID, WY, and NV at 8.7 M over 5 years (1.74M TPY)
    - CA *usage* at 2.5-3M over that same time period (500K – 600K TPY)
- Imports of fly ash by ship and rail into the broader region (all states above) estimated at 2.5 – 4.5M over 5 years (500K – 900K TPY).

Another estimate by the industry is about 1 million metric tons of fly ash consumption in California in 2020, and overall usage of about 1.25 million metric tons of SCMs in California for the same year.

Slag Cement

Background

Slag cement, formerly known as ground granulated blast furnace slag (GGBS), is a glassy material formed as the by-product during production of iron and steel in blast furnaces. As the raw materials are molten at about 2730°F, a molten slag is formed floating on top of the higher density molten metal. The slag is collected and rapidly quenched using water, transforming into a sand-like, granulated and glassy material rich in alumina, silica, and calcium oxides. The granulated material is then dried and finely ground and turned into a fine powder exhibiting cementitious properties (Kosmatka and Wilson 2016). The rate of quenching affects the amount of reactive glassy materials. Faster and more efficient quenching results in a higher concentration of the glassy materials in the resulting slag cement, hence higher reactivity. The reactivity of the material is further examined using the strength development and is used as a means of classifying the slag cement into grades of 80, 100, and 120 (ACI 233, 2017).

The use of slag cement as a cementitious material in combination with slaked lime dates back to 1774 (Mather 1957). Blended slag-portland cements were introduced in the U.S. in 1896 (ACI 233, 2017). Since the late 1950s, the use of slag cement as a separate material added to the concrete mix has gained more acceptance in many parts of the world, including the U.S. (ACI 233, 2017). When used in conjunction with portland cement, the slag cement contributes to the properties of concrete through hydraulic and pozzolanic activity. The slag cement can contribute to improvements in engineering properties and reductions in cost and carbon footprint of concrete.

Trends in Generation and Usage of Slag Cement in U.S.

In 2000, the production capacity of slag cement was estimated to exceed 2 million metric tons in North America. The production capacity in the U.S. was estimated to exceed 1.5 million metric tons, which was more than double the 1990 production capacity of about 0.7 million metric tons (ACI 233, 2017). According to the Unites States Geological Survey (USGS 2020), data are unavailable on actual U.S. ferrous slag production, but domestic slag sales in 2020 were estimated to be 14 million tons valued at about $380 million. Blast furnace slag was about 50% of the tonnage sold and accounted for 88% of the total value of slag, most of which was granulated (USGS 2020). Steel slag produced from basic oxygen and electric arc furnaces accounted for the remainder of sales. Slag was processed by 28 companies servicing active iron and steel facilities or reprocessing old slag piles at about 129 processing plants (including some iron and steel plants with more than one slag-processing facility) in 33 States, including facilities that import and grind unground slag to sell as ground granulated blast furnace slag (GGBFS).

Several domestic blast furnaces were idled in April 2020 owing to the reduced steel demand resulting from the global COVID-19 pandemic. Demand increased later in the year, and all the blast furnaces idled in 2020 reopened (USGS 2020). In recent years, U.S. blast furnaces have been closed or idled, contributing to the reduction in the domestic supply of new blast furnace slag. However, many sites have large slag stockpiles, which can allow for processing to continue for several years after the furnaces are closed or idled. The majority of U.S steel slag production is from electric arc furnaces.

According to USGS, domestic GGBFS remained in limited supply during 2020 because granulation cooling was available at only two active U.S. blast furnaces. It remained unclear if new granulation cooling installations at additional blast furnace sites would be economic. Another plant produced a limited supply of pelletized slag, but it was uncertain if additional pelletizing capacity would be added. Grinding of GGBFS was only done domestically by cement companies. Supply constraints appear to have limited domestic consumption of GGBFS in recent years. Although prices have increased, sales of GGBFS have not correlated with the increases in the quantity of cement sold since 2010.

Owing to low unit values, most slag types can be shipped only short distances by truck, but rail and waterborne transportation allow for greater travel distances. Because much higher unit values make it economical to ship GGBFS longer distances, much of the GGBFS consumed in the U.S. is imported. The majority of slag used in CA is also imported.

The import during the period of 2016-2019 was from Japan (29%), Brazil (18%), Canada (14%), Italy (12%), and other countries (27%) (USGS 2020). The import statistics for the first two months of 2021 also suggest 0.34 million tons of slag cement being imported from Japan (53%), China (34%), and Mexico (13%) (Industry Member). An overview of the total slag consumption rates in recent years is provided by the USGS and presented in Figure 8.

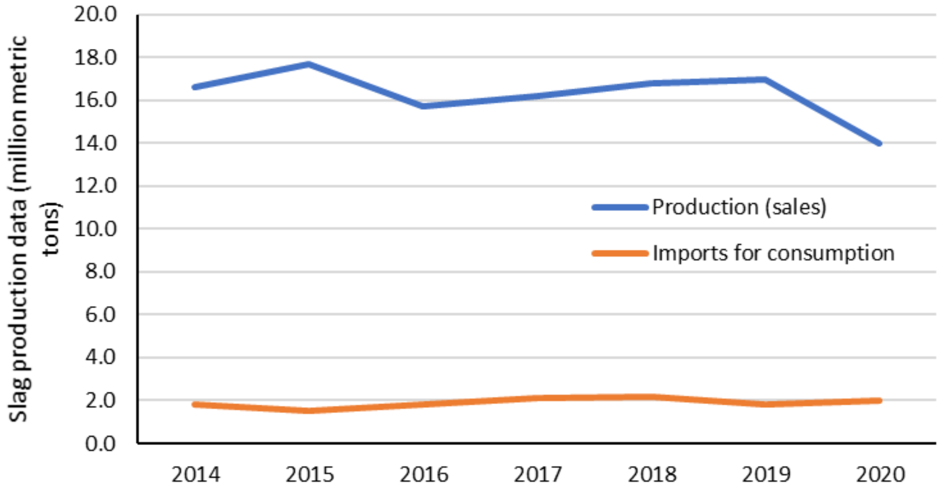

Figure 8- Slag sales data provided by the Slag Cement Association

The data provided by the Slag Cement Association (SCA) suggest increase in use (shipment) of slag cement by the association's members during the recent years, with 2019 seeing a 10.8 percent increase over 2018 totals. This marked the fourth consecutive year of double-digit percentage growth in shipping totals across the United States as shown in Figure 9.

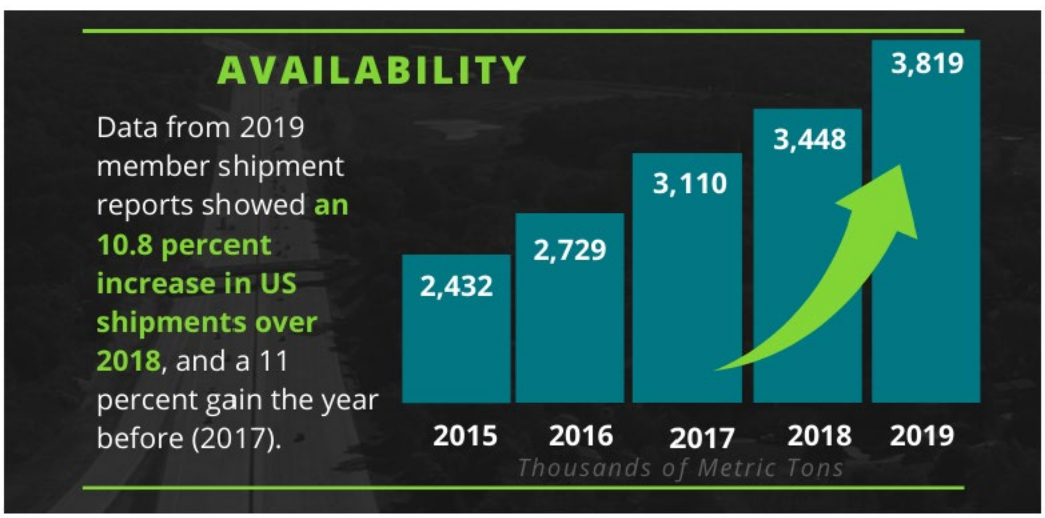

Figure 9- Slag cement sales (shipment) data provided by the Slag Cement Association

Silica Fume

Background

Silica fume, also known as microsilica and condensed silica fume, is the byproduct of silicon metals and ferrosilicate alloys in electric-arc furnaces. During the silicon metal production, a source of high purity silica (e.g. quartz or quartzite) is heated up to 3630 °F in an arc electric furnace along with wood chips and coal to remove the oxygen from the silica. The silica fumes rise as an oxidized vapor from the furnaces. When cooled down, the silica fumes condense and can be collected using bag filters. The condensed silica fume is processed afterwards to get rid of the impurities (Wilson and Kosmatka 2016).

Silica fume was first collected in Norway in 1947 (Wilson and Kosmatka 2016), with investigations on its effect on concrete properties in years to follow and one of the first large-scale structural applications in Norway in 1971 (Fiskaa et al. 1971). In late 1983, the U.S. Army Corps of Engineers incorporated silica fume in the repair of Kinzua Dam in Pennsylvania (Holland et al. 1986).

Trends in Generation and Usage of Silica Fume in U.S.

As reported by ACI committee 234 (2012), precise data on annual output of silica fume is not readily available because of the proprietary nature of the alloy industry. However, the ACI committee believes that approximately 0.9 million metric tons of silica fume are produced annually worldwide.

It is estimated (Aitcin 1983) that silica fume generation from silicon-alloy furnaces is about 30% by mass of the alloy produced. However, it is not clear that how much of the produced silica fume is used worldwide.

According to the USGS, six companies produced silicon materials in 2020, all east of the Mississippi River. Combined domestic ferrosilicon and silicon metal production in 2020, expressed in terms of contained silicon, decreased from that of 2019. One producer shut down its ferrosilicon production facility on July 1 owing to decreased demand and lower prices in part because of the global COVID-19 pandemic, as well as competition from lower priced imported ferrosilicon. Domestic production during the first 8 months of 2020 was about 11% less, on a contained-weight basis, than that during the same period in 2019. Overall, steel production, the leading use of ferrosilicon, decreased across the globe in 2020 compared with production in 2019 owing to reduced demand attributed to the global COVID-19 pandemic.

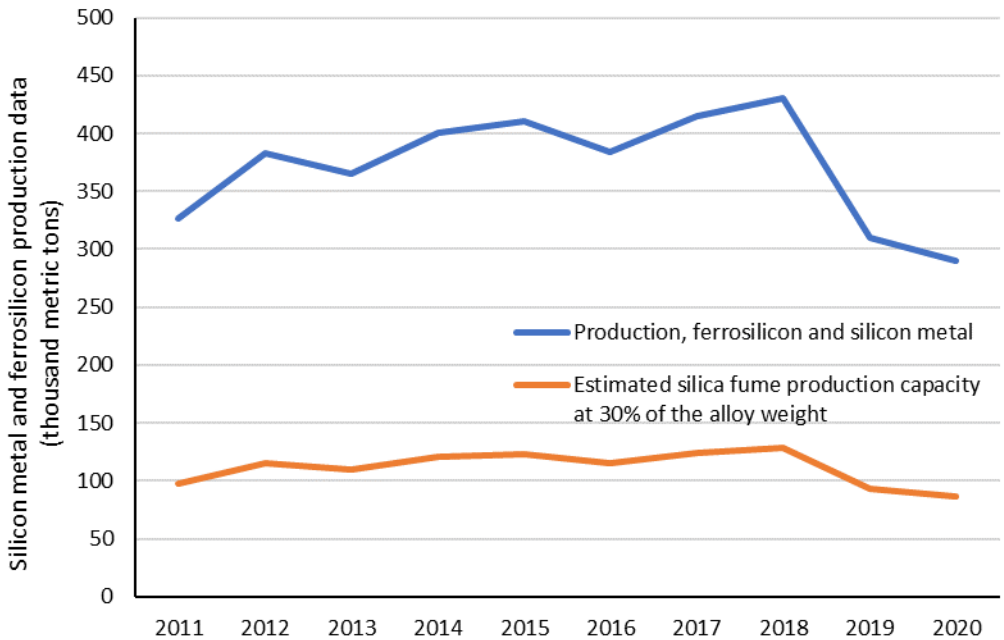

Figure 10- Ferrosilicon and silicon metal production data provided by USGS and corresponding estimations for silica fume production capacity assuming the 30% correlation introduced by Aitcin (1983)

Natural Pozzolans

Background

Use of natural pozzolans (NP) dates to 500-400 BC Greece. NP use was further developed in ancient Rome to create many structures still standing today. NPs again became a prominent component of concrete in the early 20th century when large structures such as dams relied on the performance characteristics of NPs.

Once it was discovered that fly ash had many similar qualities to NPs, fly ash began to replace NP for many applications requiring similar performance characteristics. As a by-product of coal combustion at power plants, concrete with fly ash was cheaper and provided a beneficial reuse of a waste product. Due to these characteristics, fly ash largely replaced NPs for applications requiring ASR mitigation.

NPs are often categorized as either raw or calcined. Raw pozzolans are formed from volcanic eruption ash which deposits calcined pozzolanic materials that can be extracted for use. Alternatively, calcined pozzolans are created from clays and shales in a furnace, then milled and graded to the size required for a pozzolanic reaction.

Trends and Usage of Natural Pozzolans

Unlike many of the SCMs used in Caltrans products, NPs are not a by-product but rather a primary product. Unlike by-products, NP production is dependent on NP demand which depends on specifications and alternative SCM availability. For this reason, potential production is of interest for NPs. Table 1 lists the projected NP production capacity by state for 2021 and 2022 based upon queries from members of the Natural Pozzolan Association.

Table 1. NP production by state for 2021 and 2022 (tons)

Location	2021	2022
Arizona	0	500K
California	≈100K	*
Colorado	200K	500K
Idaho	100K	200K+
Nevada	≈100K	200K+
New Mexico	150K	250K
Utah	0K	200K+
Georgia	150K	150K
Canada/Other	100K	200K+

*Construction of two new NP plants (1m tons capacity combined) is on hold pending CA-DOT approval of blended SCMs.

Illustrating the need for examining future SCM availability and specifications, construction of two NP plants are pending Caltrans approval of blended SCMs. These plants are expected to have a combined capacity of 1 million tons annually, significantly higher capacity than SCM demand by Caltrans.

Current Requirements for SCM Characteristics According to Caltrans Standard Specifications in Comparison to Other Agencies and National Standards

SCM Requirements in Section 90 of the Caltrans Standard Specifications

As previously stated, Caltrans standard specifications requires minimum SCM replacement ratios depending on the type of SCM and aggregate quality, in order to meet both durability and environmental aspects of concrete production. In addition to the two main equations used for quantifying the SCM contents, Section 90 of Caltrans standard specifications also imposes criteria regarding the quality of incorporated SCMs in terms of chemical characteristics and physical properties. A summary of these properties is provided below.

Fly Ash

Fly ash should comply with AASHTO M 295, Class F, and either of the following:

- Available alkali as Na_2O + 0.658 K_2O must not exceed 1.5 percent when tested under ASTM C311.
- Total alkali as Na_2O + 0.658 K_2O must not exceed 5.0 percent when tested under AASHTO T 105.

In addition, Caltrans considers two categories for Class F fly ash based on CaO content:

- FA with CaO limited to 10%
- FB with CaO higher than 10% and no more than 15%

Fly ash from different sources may be commingled at uncontrolled ratios if:

- Each source produces fly ash complying with AASHTO M 295, Class F
- At the time of commingling, each fly ash has:
    - Running average of relative density that does not differ from any other fly ash by more than 0.25
    - Running average of loss on ignition (LOI) that does not differ from any other fly ash by more than 1 percent
- Final commingled fly ash complies with AASHTO M 295, Class F
- Fly ash supplier is responsible for testing the commingled fly ash

Slag Cement

GGBFS must comply with AASHTO M 302, Grade 100 or 120.

Silica Fume

Silica fume must comply with AASHTO M 307, with a minimum reduction in mortar expansion of 80 percent when using the cement from the proposed mix design.

Natural Pozzolan

Raw or calcined natural pozzolans complying with AASHTO M 295, Class N, except the maximum allowable loss on ignition is 10 percent, and either of the following:

- Available alkali as Na_2O + 0.658 K_2O must not exceed 1.5 percent when tested under ASTM C311.
- Total alkali as Na_2O + 0.658 K_2O must not exceed 5.0 percent when tested under AASHTO T 105.

Metakaolin

Metakaolin must comply with AASHTO M 295, Class N, and the chemical and physical requirements for the quality characteristics shown in the Table 2 and Table 3.

Table 2- Chemical quality requirements for metakaolin in Caltrans standard specifications

Chemical quality characteristic	**Requirement (percent)**
Silicon dioxide (SiO_2) + aluminum oxide (Al_2O_3) (min)	92.0
Calcium oxide (CaO) (max)	1.0
Sulfur trioxide (SO_3) (max)	1.0
Loss on ignition (max)	1.2
Available alkalies as Na_2O + 0.658 K_2O (max)	1.0

Table 3- Physical quality requirements for metakaolin in Caltrans standard specifications

Physical quality characteristic	**Requirement (percent)**
Particle size distribution less than 45 microns (min)	95
Strength activity index with portland cement 7 days (% of control, min) 28 days (% of control, min)	 100 100

Ultra-Fine Fly Ash (UFFA)

According to Caltrans standard Specification, UFFA must comply with AASHTO M 295 requirements for Class F, and the chemical and physical requirements shown in Table 4 and Table 5.

Table 4- Chemical quality requirements for UFFA in Caltrans standard specifications

Chemical quality characteristic	**Requirement (percent)**
Sulfur trioxide (SO_3) (max)	1.5
Loss on ignition (max)	1.2
Available alkalies as Na_2O + 0.658 K_2O (max)	1.5

Table 5- Physical quality requirements for UFFA in Caltrans standard specifications

Physical quality characteristic	**Requirement (percent)**
Particle size distribution Less than 3.5 microns (min) Less than 9.0 microns (min)	 50 90
Strength activity index with portland cement 7 days (% of control, min) 28 days (%t of control, min)	 95 110
Expansion at 16 days when testing project materials under ASTM C1567[a] (max)	0.10

[a]In the test mix, at least 12 percent, by weight, of the Type II or V portland cement must be replaced with UFFA.

Rice Hull Ash

Rice hull ash can be used as an SCM only in Minor concrete applications. Rice hull ash must comply with AASHTO M 321 and the requirements for the quality characteristics shown in Table 6 and Table 7.

Table 6- Chemical quality requirements for rice hull ash in Caltrans standard specifications

Chemical quality characteristic	Requirement (percent)
Silicon dioxide (SiO_2)[a] (min)	90
Loss on ignition (max)	5.0
Total alkalies as Na_2O equivalent (max)	3.0

[a]SiO_2 in crystalline form must not exceed 1.0 percent.

Table 7- Physical quality requirements for rice hull ash in Caltrans standard specifications

Physical quality characteristic	Requirement
Particle size distribution	
Less than 45 microns (min, %)	95
Less than 10 microns (min, %)	50
Strength activity index with portland cement[a]	
7 days (min, % of control)	95
28 days (min, % of control)	110
Expansion at 16 days when testing project materials under ASTM C1567[b] (max, %)	0.10
Surface area when testing by nitrogen adsorption under ASTM D5604 (min, m^2/g)	40.0

[a]When tested under AASHTO M 307 for strength activity testing of silica fume.

[b]In the test mix, Type II or V portland cement must be replaced with at least 12 percent rice hull ash by weight.

For the purpose of calculating the equations for the cementitious material specifications, consider rice hull ash to be represented by the variable *UF*.

SCM Requirements in National Standards

The majority of the SCMs used in concrete production are by-products of other industries. These by-products are required to meet certain qualifications to ensure reactivity, uniformity, and avoid negative impacts to the cementitious system. ASTM and AASHTO have standards in place for the major SCMs. In most cases the AASHTO standard is similar to the corresponding ASTM. However, some differences can be observed in some instances. A summary of requirements on chemical composition and physical properties of the main SCMs, set by ASTM and AASHTO is presented below.

Fly Ash and Natural Pozzolans

ASTM C618 and AASHTO M295 are the two national standards that set specifications for fly ash and natural pozzolans for use in concrete. AASHTO M295 summarizes the requirements for chemical composition of Class F and Class C fly ashes, along with the chemical requirements for natural pozzolan (N). The majority of the requirements are the same as the ones set in ASTM C618, except for the loss on ignition (LOI) values, which are 5 % for AASHTO M295 and 6 % (10 % for NP) for ASTM C618. Moreover, AASHTO M295 proposes optional requirements for equivalent alkali content.

The AASHTO M295 mandatory physical requirements are the same as those stated in ASTM C618, except for strength activity requirements where 56-day values are permitted in AASHTO M295. The optional physical requirements are the same as those stated in ASTM C618, except for additional requirements on ASR in AASHTO M295.

Slag Cement

ASTM C989 and AASHTO M302 are the two national standards that set specifications for slag cement for use in concrete and mortar. ASTM C989 and AASHTO M302 specify the same 2.5 % maximum Sulfur Oxide requirement for chemical composition of the slag cement. ASTM C989 requirements for physical property can vary depending on the grade. The requirements are same as those stated in AASHTO M302.

Silica Fume

ASTM C1240 and AASHTO M307 are the two national standards that set specifications for silica fume for use in cementitious systems.

ASTM C1240 specifies the requirements for chemical characteristics of the silica fume. The same requirements are set by AASHTO M307. The mandatory physical requirements for silica fume stated by ASTM C1240 are also the same as the mandatory requirements are set by AASHTO M307.

Highly Reactive Pozzolans

AASHTO M321 includes high-reactivity pozzolans for use as a mineral admixture in portland cement concrete and mortar to fill small voids and/or where pozzolanic action is desired. High-reactivity pozzolans are defined as microsilica products with a particle size typically one to two orders of magnitude smaller than portland cement. These materials are usually supplied in undensified or densified dry form. If the material is supplied in a densified form, the tests should be performed on the as-collected undensified material before being processed into densified form.

Materials such as metakaolin, rice hull ash, zirconium fume, ultrafine fly ash, and fume from the production of 50 percent ferrosilicon (with SiO_2 less than 85 percent) are examples of high-reactivity pozzolans.

High-reactivity pozzolan shall conform to the chemical and physical requirements prescribed in AASHTO M321.

Blended SCMs

Two ASTM standards have focused on use of blended supplementary cementitious materials in construction applications:

- ASTM C1697: *standard specification for blended supplementary cementitious materials*. This standard was originally approved in 2010. The latest version was approved in December 2018 and available online since February 2019.
- ASTM D5370: *standard specification for pozzolanic blended materials in construction applications*. This standard is under the jurisdiction of ASTM Committee D34 on waste management, Subcommittee D34.03 on treatment, recovery, and reuse. This standard was originally approved in 1996. The latest version was approved in May 2014 and published in June 2014. This standard is currently withdrawn, yet still referred to by some state DOTs.

ASTM C1697-18

ASTM C1697 covers blended supplementary cementitious materials that result from the blending or intergrinding of two or three ASTM compliant SCMs, for use in concrete or mortar where hydraulic or pozzolanic action, or both, is desired. The SCMs include:

- slag cement conforming to Specification C989/C989M noted as "*S*"
- natural pozzolans and coal fly ash conforming to Specification C618 noted as "*C*" for Class C fly ash, "*F*" for Class F fly ash, or "*N*" for natural pozzolan

- silica fume conforming to Specification C1240 "noted as "*SF*"

According to ASTM C1697, the incorporation of supplementary cementitious materials as separate additions or as a manufactured blend may significantly alter the properties of fresh and hardened concrete. The user should be aware of these changes and is referred to the *ACI Manual of Concrete Practice* for information and guidelines.

For the purpose of conformance to the requirements of this specification, the blend is classified according to the predominant SCM. For blended SCMs that have no predominant constituent, the manufacturer selects the blend type. The naming practice for reporting blended supplementary cementitious materials is as follows:

SCMb- Axx/Byy/Czz

Where

SCMb is designation of the product as a blended SCM,

A is the targeted mass % of the predominant SCM in the blended SCM expressed by mass of the final blended SCM,

XX is the predominant SCM type (C, F, N, S, or SF),

B is the targeted mass % of the secondary SCM in the blended SCM expressed by mass of the final blended SCM,

YY is the secondary SCM (C, F, N, S, or SF),

C is the targeted mass % of the tertiary SCM in the blended SCM expressed by mass of the final blended SCM, required only for ternary mixtures, and

ZZ is the tertiary supplementary cementitious material (C, F, N, S, or SF)

Orders of materials under this specification will need the following information:

- Specification number
- Blend composition according to the aforementioned labeling system
- Any optional requirements

The individual constituents and the blended SCM shall be chemically analyzed using applicable analytical methods of Test Methods C311/C311M or Test

Methods C114. Analyze for major and minor oxides present in greatest quantity that together, including LOI constitutes at least 98 % of the total mass of the material. There are no chemical requirements for the blended SCM but the chemical composition of the constituents and of the blended SCM are necessary to verify blend proportions.

Blended SCMs shall conform to the optional only when specifically requested by the purchaser. Blended SCMs shall conform to the physical requirements in ASTM C1697.

The amount of pozzolan or slag cement in the finished blended SCM shall not vary from the target value by more than 62.5 percentage points for silica fume and not more than 65 percentage points for other SCMs, with a 99 % probability of compliance. To satisfy the 99 % probability of compliance, the blending process must be capable of producing a blend containing silica fume such that the standard deviation of the measured mass percentage of silica fume in the blend is less than 1 %. For constituents other than silica fume, the standard deviations of their measured mass percentages have to be less than 1.9 %. The chemical composition of the individual constituents and of the finished blended supplementary cementitious material shall be determined. The composition of the blend in terms of mass percentage of the constituents shall be calculated using the verification method proposed in the appendix of ASTM C1697.

ASTM D5370

This specification covers pozzolanic blended material for use in construction applications where the properties normally attributed to coal fly ash and raw or calcined pozzolans, like silica fume, and slag cement.

The types of pozzolanic blended materials covered by this specification are an intimate and uniform blend of two or more of the following materials: Type F – Class F fly ash; Type C – Class C fly ash; Type CKD – Cement kiln dust; Type S – ground granulated blast furnace slag; Type SF – Silica fume; Type M – Metakaolin.

Criteria for blend characteristics are dependent on the application purposes. Two main applications are considered in this standard:

- For the blended pozzolan intended for use with lime, the ASTM D5370 requires the blend to comply with the criteria set in ASTM C593- fly ash and other pozzolans for use with lime for soil stabilization.
- For the blended pozzolan intended for use in concrete, the ASTM D5370 requires the blend to comply with the criteria set in ASTM C618. Testing

should be conducted in accordance with the requirements of ASTM C311- standard test methods for sampling and testing fly ash or natural pozzolans for use in portland-cement concrete. However, carbon content can be used as a substitute for LOI.

Controlling the variations in actual blend density in comparison to the theoretical density is proposed as a non-mandatory method for controlling the blending accuracy. Tracking the concentration of a traceable admixture (e.g. fluorescein) is also proposed as a non-mandatory method for verifying the blending uniformity.

SCM Requirements in Other Agencies

Texas DOT

Item 421, Hydraulic Cement Concrete, of the Texas DOT's standard specifications require the SCMs to comply with following items:

- Fly Ash: fly ash, ultra-fine fly ash (UFFA), and modified Class F fly ash (MFFA) conforming to DMS-4610 specifications. Both Class C and Class F fly ashes are available on product list on Texas DOT.
- Slag Cement: conforming to DMS-4620 specifications.
- Silica Fume: conforming to DMS-4630 specifications
- Metakaolin: conforming to DMS-4635 specifications

A summary of key requirements in each of these specifications is provided below.

DMS-4610 requirements for fly ash

This Specification establishes the requirements, test methods, and the Fly Ash Quality Monitoring Program (FAQMP) for non-blended and blended fly ash, modified fly ash (MFA), and ground bottom ash (GBA) used in concrete products.

Non-blended fly ash is the finely divided residue or ash that remains after burning finely pulverized coal at high temperatures.

Blended fly ash is fly ash blended by interblending or intergrinding with other supplementary cementing materials including other fly ash, slag cement, natural pozzolans, etc.

MFA is a non-blended or blended fly ash produced by intergrinding with or without additional additives.

GBA is the coarse residue or ash that remains after burning finely pulverized coal at high temperature and is ground to finer material.

Non-blended and **blended** fly ash, and **GBA** must meet all the physical and chemical requirements of Table 8. Sources with average Calcium Oxide contents from the last ten samples ≥18.0% will not be allowed for use in sulfate resistant concrete.

Table 8- Mandatory requirements for blended and non-blended fly ash according to Texas DOT's standard specifications

Item	**Limit**	**Test Method**
Chemical Composition: Average CaO content of the last ten samples, %	Report Only	ASTM C 114
Sulfur Trioxide (SO_3), maximum, %	5.0	ASTM C 114
Magnesium Oxide (MgO), %	Report Only	ASTM C 114
Total Alkali Content, expressed as $NaO_{2,eq}$, %	Report Only	ASTM C 114
Strength Activity Index[1]: • 7-day, minimum, % of control • 28-day, minimum, % of control	 75 75	ASTM C 311
Fineness: Amount retained when wet-sieved on 45-µm sieve, maximum, %	34	ASTM C 311
Uniformity of Fineness: % points from average of last 10 test results or by all preceding tests if the number is less than ten	Report Only	
Water requirement, maximum % of control	105	ASTM C 311
Moisture content, maximum, %	2.0	ASTM C 311
Loss on ignition, maximum, %	6.0	ASTM C 311
Density Uniformity of Density: maximum variation from average of last 10 test results or by all preceding tests if the number is less than ten, %	Report Only 5	ASTM C 188
Autoclave Soundness, maximum, %	0.8	ASTM C 311
The Department will determine the Effectiveness in Controlling Alkali-Silica Reaction[2]: 14-day maximum expansion limit, %, when tested using a fine aggregate with an ASTM C 1260 expansion ≥0.30%,	0.10	ASTM C 1567

[1]Meeting either the 7-day or 28-day is acceptable.
[2]The Department will perform this test annually. Material producers will not have to report this testing on the material certificates.

Modified fly ash must meet the requirement of Table 8, with the exceptions and additions listed in Table 9.

Table 9- Mandatory requirements for modified fly ash according to Texas DOT's standard specifications

Item	Limit	Test Method
Strength Activity Index • 28-day, minimum, % of control	95	ASTM C 989
Fineness: Amount retained when wet-sieved on 45-µm sieve, maximum, %	10	ASTM C 311
Uniformity of Fineness: maximum variation, % points from average of last 10 test results or by all preceding tests if the number is less than ten	3	
The Department will determine the Effectiveness in Controlling Alkali-Silica Reaction[1]: 14-day maximum expansion limit, %, when tested using a fine aggregate with an ASTM C 1260 expansion ≥0.30%,	0.10	ASTM C 1567
Expansion of Mortar Bars with 50% replacement, max %	0.02	ASTM C 1038

[1] The Department will perform this test annually. Material producers will not have to report this testing on the material certificates.

DMS-4620 requirements for slag cement

This Specification establishes requirements and test methods for slag cement and the Slag Cement Quality Monitoring Program (SCQMP). Slag cement is finely ground, glassy granular material formed when molten blast-furnace slag is rapidly chilled.

Sampling will be in accordance with Tex-300-D. Testing will be in accordance with the requirements of ASTM C 989.

All slag cement must meet the requirements of ASTM C 989, Grade 100 or better.

DMS-4630 requirements for silica fume

This Specification governs the requirements and test methods for silica fume—a very fine pozzolanic material, composed mostly of amorphous silica.

Sampling and testing will be in accordance with ASTM C1240. Silica fume must meet the requirements of ASTM C1240 for chemical and physical properties.

DMS-4635 requirements for metakaolin

This Specification establishes requirements and test methods for high-reactivity metakaolin. Sampling will be in accordance with Tex-317-D. Testing will be in accordance with ASTM C 311.

Metakaolin must meet the requirements of ASTM C 618, Class N, with the modifications listed in Table 10.

Table 10- Requirements for metakaolin according to Texas DOT's standard specifications

Item	**Limit**
Silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus iron oxide (Fe_2O_3), minimum, %	85.0
Available alkalis, maximum, %	1.0
Loss on Ignition, maximum, %	3.0
Fineness: amount retained when wet-sieved on 45-μm sieve, maximum, %	1.0
Strength activity index, at 7 days, % of control	85
Increase of drying shrinkage of mortar bars at 28 days, maximum, %	0.03
Density variation in percentage points of density from the average of the last 10 samples (or fewer, provided 10 have not been tested) must not exceed ±	5

Colorado DOT

Division 700 (Materials Details) of Colorado DOT's standard specification sets the following criteria for SCMs:

Section 701.02 requirements for fly ash

Fly ash for concrete shall conform to the requirements of ASTM C618, Class C or Class F with the following exceptions:

- The LOI shall not exceed 3.0 percent.
- The CaO in Class F fly ash shall not exceed 18 percent.

Blending of pozzolans according to ASTM D5370 is permitted to meet the requirements of ASTM C618.

Fly ash shall be from a preapproved source listed on the Department's Approved Products List.

Preapproval shall include submission of a report from the supplier documenting the results of testing the fly ash from that source in accordance with the Toxicity Characteristic Leaching Procedure (TCLP) described in 40 CFR 261, Appendix II.

Section 701.03 requirements for silica fume

Silica fume for concrete shall conform to the requirements of ASTM C1240.

Section 701.04 requirements for high-reactivity pozzolans

High-Reactivity Pozzolans shall conform to the requirements of AASHTO M 321. High-reactivity pozzolans include but are not limited to metakaolin, rice hull ash, zirconium fume, ultra-fine fly ash, and fume from the production of 50 percent ferrosilicon (with SiO_2 less than 85 percent).

High-reactivity pozzolans shall meet the following optional requirement of AASHTO M 321: The sulfate expansion at 14 days shall not exceed 0.045 percent.

Section 701.05 requirements for slag cement
Slag cement shall conform to the requirements of ASTM C989. Slag cement shall be Grade 100 or Grade 120. Slag cement shall have a maximum Aluminum Oxide content of 11.0 percent.

Arizona DOT
Division X (Materials) of Arizona DOT's standard specification sets the following requirements for SCMs:

Section 1006-2.01 (C):

General: when either moderate or high sulfate resistant concrete is specified in the Special Provisions, the proposed hydraulic cement/supplementary cementitious material blend shall be tested for sulfate expansion in accordance with ASTM C1012. When moderate sulfate resistance is specified, the maximum expansion shall be 0.10 percent at six months. When high sulfate resistance is specified, the maximum expansion shall be 0.05 percent at six months or 0.10 percent at one year.

Fly ash and natural pozzolans: fly ash and natural pozzolan shall conform to the requirements of ASTM C618 for Class C, F, or N, except that the LOI for Class F and Class C shall not exceed 3 percent.
There are no direct mentions or specific additional requirements for blended products. However, the following three blended fly ashes are listed on ADOT's approved materials list as of February 11, 2021:

- SRMG/Phoenix Cement Gallup Class F Fly Ash. This is a comingled terminal blend of two ASTM Class F fly ash sources
- SRMG/Phoenix Cement 19th Ave Class F Fly Ash. This is a terminal blend of ASTM Class F and Class C fly ashes
- SRMG/Phoenix Cement Tucson Pozzolan Class F fly ash. This is a terminal blend of ASTM Class F and Class N pozzolans

Silica fume: silica fume shall conform to the requirements of ASTM C1240.

Oregon DOT

Section 02030 of Oregon DOT's standard specification sets the following criteria for SCMs:

Fly ash: furnish Class C, Class F, or Class N fly ash from the quality product list (QPL) and conforming to AASHTO M 295 (ASTM C618).
One source of Class F **UFFA** is also available on Oregon DOT's QPL, represented/manufactured by Boral Materials and listed under product name "MICRON3".

Silica fume: furnish silica fume from the QPL. Provide the silica fume as a slurry containing silica fume, water, and a high range water reducer, or as a densified powder. The silica fume portion shall conform to AASHTO M 307. Total alkalis, as equivalent Sodium Oxide (Na_2O), shall be 1.5 percent maximum.

Ground Granulated Blast Furnace Slag (GGBFS): furnish GGBFS from the QPL and conforming to AASHTO M 302.

Metakaolin: furnish metakaolin from the QPL and conforming to AASHTO M 295 (ASTM C618) Class N.

Blended: furnish blended GGBFS and fly ash from the QPL.
Please note that there is a category assigned to blended SCMs (Spec Section #02030-60) in Oregon DOT's QPL. The product is a blend of fly ash and GGBS, produced by Lafarge Corporation, and listed under the name "NEWCEM PLUS". (Based on March 8, 2021 QPL).
According to Lafarge Canada website, NEWCEM PLUS meets the requirements of ASTM C1697.

Nevada DOT

Section 702 of Nevada DOT's standard specification sets the following criteria for SCMs:

Pozzolans: pozzolanic admixtures shall be Class C, Class F, or Class N fly conforming to ASTM C618, except the LOI shall not exceed 5%. Use the pozzolan listed on the QPL.
Please note that a source of **Metakaolin** is listed under Class N pozzolan on Nevada DOT's QPL (April 15, 2021 revision).

Slag cement: slag cement shall be Grade 120 and conform to ASTM C989.

Silica fume: silica fume shall conform to ASTM C1240.

New Mexico DOT

Section 509.2.2.2 of New Mexico DOT's standard specification sets the following criteria for SCMs:

Fly Ash: Class C and F fly ashes shall comply with the requirements of ASTM C618. Class C fly ash shall not be used in concrete exposed to sulfate environments or with "potentially reactive," or "reactive" aggregate.
Additional requirements are also introduced in New Mexico DOT's standard specifications for fly ash and natural pozzolans as shown in Table 11.

Table 11- Additional requirements for fly ash according to New Mexico DOT's standard specifications

SCM Type	Material Standard	Properties	Limits		
Coal Fly Ash, and Raw or Calcined Natural Pozzolans	ASTM C618	Class	N	F	C
		Sum of Al_2O_3, SiO_2, and Fe_2O_4, min	75%	85%	50%
		Loss on ignition, max	5%	3%	3%
		Magnesium Oxide (MgO), max	5%	5%	5%
		Sulfur Trioxide (SO_3), max	3%	3%	3%
		Available alkalis as Na_2O + 0.658 K_2O, max	1.5%	1.5%	1.5%
		Calcium Oxide (CaO), max	As approved	8%	50%

There are no direct mentions or specific additional requirements for **blended** products. In addition, the NMDOT's specifications requires each cementitious material to be stored separately. However, the following fly ash is listed on NMDOT's approved materials list as of June 08, 2020:

- SRMG/Phoenix Cement Gallup Class F Fly Ash. Based on the data previously found for Arizona DOT, this is a comingled terminal blend of two ASTM Class F fly ash sources

UFFA: UFFA shall comply with ASTM C618, Class F.
Additional requirements are also introduced in New Mexico DOT's standard specifications for UFFA as shown in Table 12.

Table 12- Additional requirements for UFFA according to New Mexico DOT's standard specifications

SCM Type	Material Standard	Properties	Limits
UFFA – in addition to the requirements for Class F fly ash	AASHTO M 321	Accelerated Pozzolanic Activity Index,	
		7-day	85%
		28-day	100%
		Particle size distribution	
		Less than 2.25 µm	50%
		Less than 8.5 µm	90%
		Fineness, retained on 45 µm wet sieve, max	5.0%
		Moisture content, max	1.0%

Natural or calcined natural pozzolans: shall comply with ASTM C618, Class N. Additional requirements are also introduced in New Mexico DOT's standard specifications as previously show in Table 11.

Metakaolin: shall comply with ASTM C618, Class N. Additional requirements are also introduced in New Mexico DOT's standard specifications for metakaolin as shown in Table 13.

Table 13- Additional requirements for metakaolin according to New Mexico DOT's standard specifications

SCM Type	Material Standard	Properties	Limits
Metakaolin	ASTM C618	Silicon dioxide (SiO_2) + aluminum oxide (Al_2O_3), min	92%
		Calcium oxide (CaO), max	1.0%
		Sulfur trioxide (SO_3) max	1.0%
		Loss on ignition, max	1.2%
		Available alkalis as Na_2O + 0.658 K_2O, max)	1.5%
		Accelerated Pozzolanic Activity Index,	
		7-day	85%
		28-day	95%
		Fineness, retained on 45 μm wet sieve, max	5.0%

GGBFS: shall comply with ASTM C989, Grade 100 or 120

Silica fume: shall comply with ASTM C1240. Additional requirements are also introduced in New Mexico DOT's standard specifications for silica fume as shown in Table 14.

Table 14- Additional requirements for silica fume according to New Mexico DOT's standard specifications

SCM Type	Material Standard	Properties	Limits
Silica Fume	ASTM C1240	Reduction in mortar bar expansion when used with cement in the proposed mix design, min	80%

Kansas DOT

Division 2000 of Kansas DOT's standard specification sets the following criteria for SCMs:

Fly ash: according to Section 2004 of Kansas DOT's standard specifications, fly ash for use in concrete needs to comply with the chemical and physical requirements of ASTM C 618, Class C or Class F, except the LOI may not exceed 3.0%. The supplementary optional physical requirements apply, except that with the "Effectiveness in Controlling Alkali-Silica Reaction," the expansion of the test mixture as a percentage of the low-alkali cement control at 14 days may not exceed 120%. This testing should be conducted with 15% fly ash and a Type I/II cement with an alkali content between 0.40% and 0.44%.

Silica fume: according to Section 2006 of Kansas DOT's standard specifications, silica fume should comply with requirements of ASTM C1240.

Slag cement: according to Section 2007 of Kansas DOT's standard specifications, slag cement should comply with requirements of ASTM C989.

Blended SCMs: Section 2008 of Kansas DOT's standard specifications is devoted to blended SCMs for use in concrete and sets the following requirements:

- All individual SCMs to be blended must be prequalified according to DIVISION 2000 (above mentioned requirements for fly ash, slag cement, and silica fume).

- Provide material that complies with the chemical and physical requirements of **ASTM C 1697**, except the LOI may not exceed 3.0%. The supplementary optional physical requirements apply, except that with the "Effectiveness in Controlling Alkali-Silica Reaction," the expansion of the test mixture as a percentage of the low-alkali cement control at 14 days may not exceed 120%. Conduct this testing with 15% blended supplementary material and a Type I/II cement with an alkali content between 0.52% and 0.60%. Do not vary the amount of pozzolan or slag cement in the finished blended supplementary cementitious material from the target value by more than 2.5% for silica fume and not more than 5% for other supplementary cementitious materials.

- The quality-monitoring program must comply with the minimum sampling and testing frequencies established for the individual materials being blended. If the required sampling and testing frequencies of two or more SCMs vary, the sampling and testing plan of the SCM with the higher frequency will govern.

Oklahoma DOT

Section 702 of Oklahoma DOT's standard specification sets the following criteria for SCMs:

Fly ash: provide fly ash for PCC in accordance with AASHTO M 295, Class C or Class F. Provide fly ash for PCC from one source (power plant).

Slag cement: provide slag cement in accordance with AASHTO M 302, Grade 100 or Grade 120. Provide slag cement from one source only (plant) in the PCC.

Silica fume: provide silica fume in accordance with of ASTM C 1240. Provide silica from one source (plant).

State Specifications Summary

Each state department of transportation SCM specification was reviewed to determine common as well as innovative practices. The type of SCMs allowed as well as the national specifications applied were noted. Common alterations of the national standards were also noted. Practices under consideration for relieving future supply shortage issues were also noted.

Several commonalities among state requirements were found to contrast with Caltrans requirements. Class C fly ash is allowed in 44 states. National standards for fly ash were commonly altered with state specification language to set different maximum LOI and maximum portland cement replacement for each SCM. With 12 states, the most common max fly ash LOI to which state specifications changed is 3%. Maximum portland cement replacement levels varied, with many states setting maximums below the Caltrans minimum of 25%. Only 12 states allow Natural Pozzolans and only eight allow Metakaolin. Most states set maximum replacement limits, with many setting a maximum below the minimum Caltrans limits.

Four states allow use of ASTM C1567 to qualify a mix designed for some aspect of ASR mitigation. This practice introduces a performance-based aspect to the acceptance criteria with the limitations on mix design varying by state.
At least nine states allow blended SCMs, either explicitly in their specifications or through an AML.

States allowing **blended SCMs**:

- Based on ASTM C1697: OR (slag + fly ash), KS, WA, ID
- Based on ASTM D5370: CO (to meet C618)
- States with no direct mention of allowing blended SCMs in specifications, but having blended SCM sources on AML: NM (Gallup F ash; combination of two Class F ashes), AZ (F+F, F+C, and F+N).
- CA allows commingling of fly ashes and has a blended fly ash (Gallup F ash; combination of two Class F ashes) on AML.
- TX is allowing blended and modified fly ash in specifications, with no direct mention of a reference standard.

Table 15- States using ASTM standard for their main requirements

FA-C	FA-F	NP	Slag	SF	Metakaolin	UFFA
C618			C989	C1240	C618	C618
CO, AZ, FL, IN, IA, KY, MI, MN, NE, NJ, NC, OH, VA, WV, WI, WY, OR, NV, NM, KS	CO, AZ, FL, IN, IA, KY, MI, MN, NE, NJ, NC, OH, VA, WV, WI, WY, OR, NV, NM, KS	AZ, OR, NV, NM, IA, LA, WI, WV	TX, CO, NV, NM, KS, FL, IN, IA, KY, MI, OH, RI, SC, VA, WI, WY	TX, CO, AZ, FL, KY, MD, MI, NE, NC, OH, OK, SC, NV, NM, KS, OK	TX, OR, NV, FL	NM

Table 16- States using AASHTO standard for their main requirements

FA-C	FA-F	NP	Slag	SF	Metakaolin	UFFA	RHA
M295			M302	M307	M321/295	M321/295	M321
OR, OK, AK, AR, AL, CT, DE, GA, IL, LA, MD, MS, MO, MT, NH, NY, ND, OK, PA, RI, SC, SD, TN, UT, VT, WA	CA, OR, OK, ID, ME, MA, AK, AR, AL, CT, DE, GA, IL, LA, MD, MS, MO, MT, NH, NY, ND, OK, PA, RI, SC, SD, TN, UT, VT, WA	CA, OR, GA, PA, UT	CA, OR, OK, AK, AR, AL, CT, DE, GA, ID, IL, LA, ME, MD, MA, MN, MS, MO, MT, NH, NJ, NY, NC, OK, PA, RI, TN, VT, WA, WV	CA, OR, AK, AL, DE, GA, ID, IL, IN, LA, ME, MA, MS, MT, NJ, NY, PA, RI, TN, UT, VT, VA, WA, WV, WY	CA, CO, OR, IL, VA,	CA, CO, NM	CA, CO

Mitigation Strategies

Pros and Cons of SCMs

Class F Fly Ash

- **Pros:**
  - Works well in hot and dry areas where workability may become an issue.
  - Reduces permeability, which is particularly important in coastal and desert locations common to California.
  - Mitigates ASR.
  - Reduces heat generated, mitigating heat-induced delayed ettringite formation. This is particularly important for mass concrete.
  - Relatively low cost.
- **Cons:**
  - Supply depends on Coal Power Generation which is prone to fluctuations, resulting in frequent regional shortages and uncertain future supply.

Class C Fly Ash

- **Pros:**
  - There are class C sources local to California.
  - Relatively low cost.
- **Cons:**
  - Limitations on CaO percentage.
  - Requires more replacement in concrete mix to mitigate ASR.
  - Many sources have high SO_3 levels.

Slag

- **Pros:**
  - Improves sulfate resistance, prevents ASR, and reduces permeability.

- **Cons:**
    - Imported.
    - Limited supply.

Silica Fume

- **Pros:**
    - Significantly reduces permeability and ingress of ions, leading to greater durability and resistance to chlorides, sulfate, and ASR.
    - Produces higher strength concrete and is often considered for high performance concrete.
- **Cons:**
    - Health risks for respiratory contact when in dry form.
    - Detrimental to workability, high fineness increases water requirement and impacts time during which workability is retained.
    - Low supply.
    - High water retention reduces bleeding, sometimes resulting in plastic shrinkage cracking.
    - Increases heat generation of concrete.

Metakaolin

- **Pros:**
    - Produces higher strength concrete.
    - Reduces permeability, increases resistance to ASR and chemicals.
- **Cons:**
    - Low supply.
    - Lack of production local to California.

Rice Hull Ash

- **Pros:**
    - Produces higher strength concrete.
    - Reduces permeability, increases resistance to ASR and chemicals.

- **Cons:**
    - Lack of production local to California.
    - Low density increases shipping costs.

Natural Pozzolans

- **Pros:**
    - Available sources in California.
    - Large supply potential.
    - Mitigates ASR.
    - World-wide use.
    - Some amount available as a byproduct from industrial processes.
- **Cons:**
    - Increased water demand, admixtures may be necessary.
    - Primary product NP requires drying and grinding.
    - Learning curve for California contractors.
    - Characteristics vary with respect to origin.

Recycled Glass

- **Pros:**
    - Recycled product.
    - Produces higher strength and durability concrete.
- **Cons:**
    - Not readily available in California.
    - High initial investment required.
    - Not all glass can be used.

Lithium

- **Pros:**
    - Mitigates ASR.

- **Cons:**
  - Low supply on west coast.
  - Energy intensive to produce.
  - Doesn't provide other benefits.
  - Demand from other industries outpaces supply.

Pros and Cons Reclaimed Fly Ash

Significant portions of total fly ash produced from power plants have been deposited into landfills. In the US alone, the American Coal Ash Association estimates at least 2.5 billion tons of usable fly ash is in landfills or ponds. Due to fly ash shortages and potential insufficient future supply from the changing energy market, reclaiming landfilled fly ash has potential to supply the need of concrete production for decades to centuries. Reclaiming fly ash will also provide beneficial reuse for a waste product.

ASTM E3183 provides a standard process for reclaiming fly ash. ASTM C618 outlines the requirements for the finished product. Landfills are surveyed, similarly to new alluvial sources. If the fly ash in the landfill is the correct type and has a large enough quantity, typically 1 to 10 million tons may be recoverable from each site. Many landfills chosen for reclamation will produce 100,000 to 400,000 tons per year to market with a 50 to 100 tons per hour processing rate. These sites recover from 50 to 75% of the landfilled fly ash. Currently there is one reclamation project in Arizona.

- **Pros:**
  - Potential supply can meet concrete production needs for decades to centuries at current production levels.
  - Reclamation projects have been taking place in several states including Pennsylvania, Alabama, and the Carolinas.
  - The quality of the end-product is within the range of acceptable quality for most applications and is, in some cases, higher quality than fly ash taken directly from some power plants.

- **Cons:**
  - Currently there are limited reclamation projects taking place in the western United States.
  - Harvested fly ash is significantly more expensive than fly ash taken directly from the power plant. The air quality permits for reclamation

are similar to those required for an asphalt plant; this can increase costs and development time of reclamation projects.
    - New truck or rail routes would be required from each reclamation site.

Pros and Cons of Remediated SCMs

SCMs that do not meet specification requirements can be blended with other SCM products to form a blend conforming to specifications. Examples of SCMs with which nonconforming fly ash is blended with include specification conforming fly ash, other nonconforming fly ash, natural pozzolans, etc. Other non-conforming biproducts such as sand and clay have been calcined and combined to form an SCM blend similar to metakaolin with more strength than fly ash, less than typical metakaolin, but neutral water demand. Approximately 40% of the fly ash produced in the United States gets used. By blending, much of the discarded fly ash can be utilized to increase supply. Landfilled, nonconforming fly ash is also a candidate for upcycling.

Remediated SCM projects are taking place in Colorado and Texas. Two plants in Colorado combined provide 500k tons of NP blended with fly ash that, alone, does not meet specification requirements. A similar plant in Texas is under development to open in 2022 is projected to produce an additional 500-600k tons per year. Several states near these sites (CO, TX, OK, KS, NE) include this remediated SCM on their list of approved products. The product is accepted based upon specifications for Class F fly ash, in some cases with additional requirements.

- **Pros:**
    - Potential for greatly increased supply of fly ash.
    - In some cases, lower variability of quality due to mixing with consistent quality product, for example fly ash can have highly variable quality. When blended with natural pozzolans, the quality variability of the blend can be less than fly ash alone.
    - Beneficial use of fly ash from landfills
    - Potential for production of upcycled SCMs local to California that can meet demand.
- **Cons:**
    - Caltrans does not currently recognize remediated products in specifications.

- Blending fly ash with natural pozzolans increases water demand above that of fly ash only.

Pros and cons associated with use of blended SCMs (in progress)

Blended SCMs are a designed product that can take advantage of the positive aspects of each constituent and reduce or eliminate negative aspects.

- **Pros:**
  - Can bring out of specification materials into specification increasing overall SCM supply.
  - Can use one SCM's positive attribute to compensate for another SCM's properties.
  - May be able to utilize smaller sources of SCMs that currently aren't viable because of quantity or consistency of supply.
  - SCMs can be custom blended for local markets and environmental conditions.
  - Has the potential to bridge the fly ash supply over time.
  - ASTM has a specification C1697 for blended SCMs. It currently only allows Class N pozzolan, Class F fly ash, Class C fly ash, silica fume and slag into blend. The other ASTM specification (ASTM D5370) is withdrawn but can be used as a general guide.
- **Cons:**
  - Caltrans does not currently recognize blended SCMs in their specifications (PMPC's Blended SCMs workgroup is investigating the feasibility of adoption by Caltrans – the proposal would allow for storage of blended SCMs into a single storage silo).
  - Need to develop acceptance/testing criteria from Caltrans side.
  - Industry will have to develop consistent processes to blend and certify the material that would create a consistent quality.

Pros and cons associated with use of blended cements (in progress)

Blended hydraulic cements consist of two or more inorganic constituents (at least one of which is not portland cement or portland cement clinker). Blended hydraulic cement can be a "binary" blend which consists of portland cement with either a slag, a pozzolan or a limestone or a "ternary" blend consisting of a portland cement with either a combination of two different pozzolans, slag and a pozzolan, a pozzolan and a limestone, or a slag and a limestone.

- **Pros:**
    - Many different qualities possible with a cement and different SCMs.
    - Wouldn't require separate storage silos.
- **Cons:**
    - Depending on what constituents make up the blend, the GHG emissions associated with the blend will vary.
    - Not all blends are currently allowed by Caltrans specifications. (The use of blended cements complying with AASHTO M240 is being addressed in portland-limestone cement workgroup and new cement types will be allowed in Caltrans applications.)

Potentials for performance-based concrete mix designs to reduce cementitious materials content and/or SCM replacement rates (Scoping document)

A performance-based specification would allow contractors to optimize the SCM content for the specific aggregate used and promote more efficient use of aggregates and SCMs.

- **Pros:**
    - Will provide contractors with additional flexibility in the use of SCMs by adopting a performance-based mitigation strategy for project-specific concerns.
- **Cons:**
    - Need to ensure maintaining the Department's durability and sustainability objectives.
    - Several elements need to be in place in order to add performance based options, including (1) required performance criteria, (2) sampling and testing method, (3) acceptance criteria, (4) actions to take if acceptance criteria are not met, (5) an implementation plan.
    - Can result in more testing from contractor side and needs planning in advance.

Product limiting specifications

An example of such limitations was the loss on ignition (LOI) values set for natural pozzolans in the 2018 standard specifications, where the LOI was limited to 5% for natural pozzolans. The subject was studied, and the requirements were modified to allow for an increased LOI of up to 10% for natural pozzolans in the RSS 04/16/2021.

Another instance could be the use of Class C fly ash. Should the material be available, there might be an option to investigate the feasibility of using Class C fly ash along with innocuous aggregates in situations where we are not dealing with aggressive exposure conditions. Another application could be minor concrete works.

Revisiting the standard specifications for metakaolin was also suggested by the industry members of the team. There is a new producer of metakaolin in CA (within the last year) whose material is around 95% SAI in 7 days and 105% SAI in 28 days. Based on the Caltrans prescription (100% SAI at 7d), this material, which is more effective at mitigation and strength performance than fly ash, would not qualify for the Caltrans Authorized Material List. It may be useful to the concrete industry and Caltrans to indicate that Metakaolin (MK) must comply with AASTHO M321. The most highly effective, higher strength-higher mitigation MKs, do not meet M295 or C618 water requirement specifications. The most effective MKs are in the 120% range on water demand. M321 specifically calls out MK as a 'High-Reactivity Pozzolan' for which M321 was designed. There is no minimum water requirement in M321.

Products In-Development

There are several products being developed that may alleviate the impact of SCM shortages to Caltrans. The following list presents in-development products perceived to be viable options withing the next five years.

- **Calcined/Vitrified Shale and Clay** – A product similar to fly ash, but with more consistent availability. However, supply is limited and currently no production exists in California, despite presence of mineral sources.
- **Treated Fly Ash** – CO_2 treated fly ash forms a product with increased strength, ASR mitigation, and improved sulfate expansion while sequestering CO_2. This may expand the fly ash considered suitable for concrete production.
- **New hydraulic cements** – New formulations of hydraulic cement may allow use of alternative SCMs and reduce environmental impact of concrete production.

- **Liquid SCMs** – Similar properties to an SCM such as fly ash, while requiring a lower volume. This could significantly reduce cost and environmental impact of shipping. Liquid SCMs also increase effective storage capacity at facilities.

Conclusions

This document reports on the state of Supplementary Cementitious Material (SCM) supply and projected future SCM supply to California and nationally. Details of the recent fly ash shortages to California were recorded. Standards of SCM use among other states and in national standards were compiled for comparison and mitigation strategies were explored. This information is meant to serve as justification for efforts to improve California's capacity to handle future shortages. This report will also help to guide agencies with deciding which strategies to pursue while adapting to a changing SCM market.

Some mitigation approaches are currently being investigated by Caltrans for potential future implementation. Others will be explored by one or more Caltrans committees to determine viability in improving Caltrans' response to a future shortage, while allowing us to maintain our quality standards.

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