Supplementary Cementitious Materials and Blended Cements to Improve Sustainability of Concrete Pavements

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Introduction

Because of its relatively low-cost, widespread availability, versatility, and hallmark longevity, hydraulic cement concrete (HCC) is the most widely used building material on the planet. In transportation infrastructure alone, concrete is used in a variety of applications, including bridges, hydraulic structures, retaining walls, barriers, curbs and gutters, sidewalks, and, of course, pavements.

Unfortunately, this versatility comes with an environmental price tag. For example, it is recognized that the material acquisition, transportation, and processing inherent in delivering concrete to a job site has significant environmental impacts in terms of energy use, consumption of non-renewable resources, and greenhouse gas (GHG) emissions.

The latter receives particular emphasis because GHG emissions are associated with global climate change, which is expected to grow in importance in the coming years (TRB 2010). Given these considerations, there is a compelling need to develop strategies to reduce the environmental impacts of concrete used in transportation infrastructure, including pavements, while maintaining its economic and social value.

This Tech Brief describes how supplementary cementitious materials (SCMs) and blended cements are used in paving concrete as one way of increasing the overall sustainability of concrete mixtures. This brief begins by discussing how cement and concrete production impacts sustainability, presents the types of SCMs and blended cements that can be used effectively in concrete pavements, answers the question of why SCMs and blended cements should be used, and provides guidance on how they should be used. This Tech Brief finishes by discussing current trends that may impact the future availability of SCMs and blended cements.

Portland Cement, Concrete, and Sustainability

It was common during most of the early and mid-twentieth century to use paving mixtures that employed portland cement (specified under AASHTO M 85/ ASTM C 150) as the sole binder. From the early 1980s onward, there was an increase in the use of SCMs, such as fly ash (specified under AASHTO M 295/ ASTM C 618) and slag cement (specified under AASHTO M 302/ASTM C 989), and, today, SCMs are used routinely in concrete paving mixtures to provide economy, improved workability, enhanced long-term strength and durability, and increased sustainability (Van Dam et al. 2012).

From an environmental perspective, one of the main advantages of increased SCM or ground limestone use is that it can reduce the estimated 0.918 tons of carbon dioxide (CO_2) that are emitted on average for every ton of AASHTO M 85 portland cement manufactured in the US. (Marceau et al. 2010). The U.S. Environmental Protection Agency (US EPA 2013) estimated that cement production was responsible for approximately 35 million tons of CO_2 equivalent, or just under 0.6 percent of the total US GHG emissions, in 2011. Studies have shown that for typical concrete, roughly 85 percent of the energy and 90 percent of the GHG emissions associated with concrete production are results of the manufacturing of portland cement (Choate 2003, Marceau et al. 2007). Some reduction of GHG emissions can be achieved through improved plant efficiency, but roughly half of the CO_2 emitted is from decomposition of the raw materials, thus limiting the potential improvement through this route alone.

Therefore, the most effective strategy to reduce the GHG emissions associated with concrete without negatively affecting concrete performance is to reduce the amount of portland cement clinker (the nodules produced in a cement kiln) used as a binder in concrete. For example, since the late 2000s, AASHTO M 85 allows up to 5 percent high-quality natural limestone to be interground with the clinker, which has the potential to lower the overall GHG emissions associated with portland cement to approximately 0.90 tons CO_2 per ton of cement. On a larger scale, the amount of clinker used as binder can be reduced significantly by replacing portland cement with SCMs, either by adding SCMs to the concrete mixture at the concrete plant or with the use of blended cements specified under AASHTO M 240. The use of blended cements is the focus of this Tech Brief.

Types of Supplementary Cementitious Materials

SCMs are materials that, when blended with portland cement, contribute to the properties of concrete through hydraulic activity, pozzolanic activity, or both (Kosmatka and Wilson 2011). Hydraulic activity occurs when phases in the SCM chemically react with water, forming cementitious hydration products similar to those formed through hydration of portland cement. This is in contrast to pozzolanic activity, which is characterized by the reaction between siliceous or aluminosiliceous material in the SCM with calcium hydroxide (a reaction product from the hydration of portland cement), forming calcium silicate hydrate and other cementitious compounds. Calcium silicate hydrate is a more desirable hydration product and thus the pozzolanic reaction is considered to have a positive impact on the long-term properties of the hardened concrete.

SCMs can be blended with portland cement by the cement manufacturer and sold as blended cement under AASHTO M 240 or added at the concrete plant by the concrete producer. SCMs that are used commonly in paving concrete include fly ash (specified under AASHTO M 295) and slag cement (specified under AASHTO M 302). Natural pozzolans (also specified under AASHTO M 295 as Class N) are used less commonly and it is possible that small amounts of silica fume (specified under AASHTO M 307/ASTM C 1240) could also be used as one component of a ternary mixture. Table 1 summarizes properties of these common SCMs, noting that calcined clay, shale, and metakaolin are classified as Class N natural pozzolans.

Tables 2 and 3 summarize how each SCM impacts the behavior of fresh and hardened concrete, respectively.

Table 1. Typical chemical compositions and select properties of common SCMs (Taylor et al. 2006 from Kosmatka et al. 2002)

	Type I cement	Class F fly ash	Class C fly ash	GGBF slag	Silica fume	Metakaolin
Silica (SiO_2), %	22.00	52.00	35.00	35.00	90.00	53.00
Alumina (Al_2O_3), %	5.00	23.00	18.00	12.00	0.40	43.00
Iron oxide (Fe_2O_3), %	3.50	11.00	6.00	1.00	0.40	0.50
Calcium oxide (CaO), %	65.00	5.00	21.00	40.00	1.60	0.10
Sulfate (SO_4), %	1.00	0.80	4.10	9.00	0.40	0.10
Sodium oxide (Na_2O), %	0.20	1.00	5.80	0.30	0.50	0.05
Potassium oxide (K_2O), %	1.00	2.00	0.70	0.40	2.20	0.40
Total eq. alkali (as Na_2O), %	0.77	2.20	6.30	0.60	1.90	0.30
Loss on ignition, %	0.20	2.80	0.50	1.00	3.00	0.70
Blaine fineness, m^2/kg	350.00	420.00	420.00	400.00	20,000.00	19,000.00
Relative density	3.15	2.38	2.65	2.94	2.40	2.50

Table 2. Effects of SCMs on the properties of fresh paving concrete (Taylor et al. 2006)

	Fly ash				Natural pozzolans		
	Class F	Class C	GGBF slag	Silica fume	Calcined shale	Calcined clay	Metakaolin
Water requirements	↓↓	↓↓	↓	↑↑	↔	↔	↑
Workability	↑	↑	↑	↓↓	↑	↑	↓
Bleeding and segregation	↓	↓	↕	↓↓	↔	↔	↓
Air content	↓↓ *	↓ *	↓	↓↓	↔	↔	↓
Heat of hydration	↓	↕	↓	↔	↓	↓	↓
Setting time	↑	↕	↑	↔	↑	↑	↔
Finishability	↑	↑	↑	↕	↑	↑	↑
Pumpability	↑	↑	↑	↑	↑	↑	↑
Plastic shrinkage cracking	↔	↔	↔	↑	↔	↔	↔

Sources: Thomas and Wilson (2002); Kosmatka et al. (2003)

* Effect depends on properties of fly ash, including carbon content, alkali content, fineness, and other chemical properties.

Key:
↓ reduced
↓↓ significantly reduced
↑ increased
↑↑ significantly increased
↔ no significant change
↕ effect varies

Table 3. Effects of SCMs on the properties of hardened paving concrete (Taylor et al. 2006)

	Fly ash				Natural pozzolans		
	Class F	Class C	GGBF slag	Silica fume	Calcined shale	Calcined clay	Metakaolin
Early strength	↓	↔	↓	↑↑	↓	↓	↑↑
Long-term strength	↑	↑	↑	↑↑	↑	↑	↑↑
Permeability	↓	↓	↓	↓↓	↓	↓	↓↓
Chloride ingress	↓	↓	↓	↓↓	↓	↓	↓↓
ASR	↓↓	↕	↓↓	↓	↓	↓	↓
Sulfate resistance	↑↑	↕	↑↑	↑	↑	↑	↑
Freezing and thawing	↔	↔	↔	↔	↔	↔	↔
Abrasion resistance	↔	↔	↔	↔	↔	↔	↔
Drying shrinkage	↔	↔	↔	↔	↔	↔	↔

Sources: Thomas and Wilson (2002); Kosmatka et al. (2003)

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Fly ash is an industrial by-product material produced at coal-fired power plants. As the pulverized coal combusts, mineral impurities are carried away in the flue gases, solidifying into spherical glassy particles. These particles, being roughly the same size as cement grains, are collected by electrostatic precipitators or bag filters.

In 2011, it was estimated that nearly 60 million tons of fly ash were produced in the US, of which 38 percent was beneficially used, including 14 million tons used by the cement and concrete industry (ACAA 2013a). Historically, this is a decrease in both peak fly ash production (approximately 76 million tons in 2002) and the peak utilization rate (approximately 45 percent in 2006) (ACAA 2013b). The main reason for the decrease in fly ash production and utilization was the economic slowdown but, as will be discussed, other pressures exist that will likely reduce fly ash availability in the future.

Fly ash varies in composition and mineralogy as a result of the source of coal, how it is burned, and how the ash cools. AASHTO M 295 classifies fly ash as either a Class C fly ash or a Class F fly ash based primarily on composition, where Class F fly ash has a minimum combined silicon dioxide, aluminum oxide, and iron oxide content of 70 percent whereas Class C fly ash has between 50 and 70 percent. Class F fly ash will typically have less calcium oxide than Class C, but no limit on calcium oxide is established in the specification.

The differences in composition and mineralogy are reflected in Table 1 and in the properties of fresh and hardened concrete as shown in Tables 2 and 3, respectively. Typical dosage rates for Class F fly ash for paving concrete are 15 to 25 percent by mass of total cementitious materials, whereas they are slightly higher for Class C fly ash at 15 to 40 percent (Taylor et al. 2006).

As an industrial by-product material, the composition, reactivity, and properties of fly ash are highly variable. This variability can be extreme for different classes of fly ash, for the same class of fly ash from different sources, and even for fly ash produced at the same electrical plant given that coal sources, burning techniques, and environmental technologies are changing rapidly. These differences and variability must be recognized in design and construction and rigorous testing of fly ash must be conducted on a frequent basis to ensure its continued suitability for use in concrete.

Slag cement is an industrial by-product of the iron blast furnace in which pig iron is extracted from iron ore and the remaining molten material (slag) is directed into a granulator, in which water quenches the material to form glassy, sand-like particles of amorphous oxides of calcium, aluminum, magnesium, and iron (the typical composition is shown in Table 1). These particles are then ground to a similar size as, or slightly finer than, portland cement.

Slag cement is reactive, either slowly in the presence of water alone or more vigorously when activated in water in the presence of sodium hydroxide or calcium hydroxide. The latter is the condition present in the pore solution of hydrating portland cement and, thus, the two react in a complementary manner.

Similar to the use of fly ash, the use of slag cement has decreased with the economic downturn in the later part of the first decade in the twenty-first century. However, this may have turned around as a number of iron furnaces restarted operations in 2010. The domestic availability of slag, in general, is in decline in the US due to closure of a number of US blast furnaces and a lack of construction of new furnaces. As of 2011, there were only four granulators installed at active blast furnaces in the US (USGS 2011).

Slag is an attractive SCM for a number of reasons. For one, the typical dosage of slag cement is higher than for fly ash, usually in the range of 25 to 35 percent of the total cementitious materials for paving concrete, although it can be used in much higher amounts (ACPA 2003, Taylor et al. 2006). Furthermore, slag creates very light-colored, highly-reflective concrete that some find aesthetically pleasing and that may help reduce the urban heat island effect. Additional features of paving concrete made with slag are summarized in Tables 2 and 3.

As an industrial by-product material, slag cement will vary from source to source, but variability for a given source is usually very low. Often the properties of the slag cement are altered slightly as a result of the fineness of the grind, with more finely-ground slag cement being more reactive.

Other SCMs, including silica fume and natural pozzolans, are sometimes used in concrete paving. Silica fume (specified under AASHTO M 307) is an ultrafine non-crystalline silica by-product of the production of silicon metals and ferrosilicon alloys that is a highly-reactive pozzolan, often used in high-performance and ultra-high-performance concrete (UHPC). Concrete containing more than a few percent replacement is often difficult to work with and silica fume is significantly higher in cost than portland cement, so its use is often restricted to applications that demand high strengths and/or low permeability.

Natural pozzolans represent a family of SCMs produced from natural mineral deposits or biomass. Some of these minerals, such as volcanic ash, are similar to what was used in ancient Rome to construct the Pantheon and aqueducts and can be used with only minimal processing. Others require calcination through heat treatment.

More recently there have been efforts

to derive commercially-viable natural pozzolans from biomass such as rice husks but, as of yet, this effort has not become commercially viable. In the US, interest in natural pozzolans is rising due to uncertainty regarding supplies of fly ash and slag cement. American Concrete Institute (ACI) 232.1R, Use of Raw or Processed Natural Pozzolans in Concrete (2012) provides an excellent synopsis on the history and use of natural pozzolans in concrete.

Summarizing, when replacing cement with SCMs (e.g., fly ash or slag cement) on a mass basis, an increase in paste volume occurs due to the lower specific gravity of SCMs compared to portland cement. This in turn results in improved workability and slightly-reduced water demand. One potential negative effect of SCM use on fresh concrete is that SCMs often result in a reduction in air-entraining efficiency, so this must be monitored carefully during construction.

Most SCMs (other than some Class C fly ashes) will result in a significant reduction in the heat of hydration, which can be used effectively in the summer to reduce built-in curl and early-age cracking. On the other hand, the lower heat of hydration can result in increased setting time, particularly during cold weather placements, which increases the risk of plastic shrinkage cracking. Along these same lines, early strength gain is generally retarded when using most SCMs, but the long-term strength gain is increased. And, finally, most SCMs reduce permeability and chloride ion ingress in concrete and can be used to effectively mitigate alkali-silica reactivity (ASR) (Thomas et al. 2008) and sulfate attack (ACI 2008). Class C fly ashes can be the exception to some of these improvements. In all cases, thorough testing should be conducted throughout the mixture proportioning and construction phases of the project to ensure that the concrete containing SCMs is performing as desired.

Blended Cements

Blended cements, specified under AASHTO M 240 (ASTM C 595), Standard Specification for Blended Hydraulic Cements, are produced by cement manufacturers through either intergrinding or blending portland cement with fly ash, natural pozzolans, slag cement, and/or limestone. The blended cement can be a binary system, made with portland cement and one other material, or a ternary combination of portland cement and two other materials, classified as follows:

- Type IP(X) – The P indicates that this is portland-pozzolan cement in which X denotes the targeted percentage of pozzolan (which can constitute up to 40 percent by mass of the blended cement) expressed as a whole number by mass of the final blended cement. For example, a Type IP(20) is a blended portland-pozzolan cement that contains 20 percent pozzolan.
- Type IS(X) – The S indicates that this is portland-slag cement in which X denotes the targeted percentage of slag cement (which can constitute up to 95 percent by mass of the blended cement) expressed as a whole number by mass of the final blended cement. Thus, for example, a Type IS(35) is blended portland-slag cement that contains 35 percent slag cement.
- Type IL(X) – The L indicates that this is portland-limestone cement in which X denotes the targeted percentage of limestone (which can constitute up to 15 percent by mass of the blended cement) expressed as a whole number by mass of the final blended cement. Thus, for example, a Type IL(12) is blended portland-slag cement that contains 12 percent slag cement.
- Type IT(AX)(BY) – The T indicates that this is ternary blended cement in which the A refers to the type of pozzolan, slag, or limestone (either P for pozzolan, S for slag cement, or L for limestone) that is present in the larger amount by mass and the B refers to the additional material, either P for pozzolan, S for slag cement, or L for limestone that is present in the lesser amount. The X and Y refer to targeted percentage of mass for constituent A and B, respectively. For example, a material designated as Type IT(S25)(P15) contains 60 percent portland cement, 25 percent slag cement, and 15 percent pozzolan. If the percentages of the SCMs are the same, the materials are listed in alphabetical order, i.e., Type IT(L10)(S35) which has 55 percent portland cement, 10 percent limestone, and 35 percent slag cement. Two different pozzolans can also be blended together to create a Type IT(PX)(PY). In no case can the percent limestone exceed 15 percent by mass of the blended cement, and the combined pozzolan percentage cannot exceed 40 percent. Furthermore, the combined mass of limestone, pozzolan, and slag cement shall be less than 70 percent by mass of the blended cement.

Typical replacement rates for blended cements are 10 to 12 percent for Type IL, 15 to 25 percent for Type IP, and 30 to 50 percent for Type IS (based on Van Dam and Smith 2011). The composition of a Type IT can vary significantly depending on the characteristics of the various SCMs used.

In addition to the above designations, blended cements can be further labeled with the following suffixes:

- A to indicate air-entrained material
- MS or HS to indicate moderate or high sulfate resistance, respectively
- MH or LH to indicate moderate or low heat of hydration

Type IL portland-limestone cements were added to AASHTO M 240 in 2012 and thus are relatively new to the market. This followed the allowance of intergrinding portland cement clinker with up to 5 percent limestone allowed in AASHTO M 85 since 2007.

Portland-limestone cements have been used in Europe for more than 25 years, with the most popular type of cement used in Europe containing up to 20 percent limestone. Canada approved the use of portland-limestone cements containing up to 15 percent limestone in 2009. The 15 percent limit is in place to ensure the portland-limestone cement performs similarly to conventional portland cement and blended cements. At this replacement level, it is estimated that the use of portland-limestone cement reduces CO_2 emissions by up to 10 percent compared to conventional portland cement (CAC 2009).

Although the use of Type IL cement reduces CO_2 emissions, there are other advantages as well. Limestone is softer than clinker and, thus, when the two are interground, the resulting limestone particles are finer than the clinker particles. This results in improved particle distribution and packing and the fine limestone particles act as dispersed nucleation sites for the formation of hydration products. This results in a dense microstructure as hydration proceeds.

In addition, the limestone is not chemically inert, reacting with the aluminate phases present in portland cement and many SCMs to create carboaluminate phases (Matschei et al. 2007). Cement manufacturers can optimize the chemical and physical properties of Type IT blended cement to achieve equivalent, or even improved, performance to that obtained using conventional AASHTO M 85 portland cement. Several North American field studies have demonstrated that Type IL cements can be used similarly to AASHTO M 85 and other AASHTO M 240 cements in the construction of concrete pavements (Thomas et al. 2010, Van Dam et al. 2010).

Advantages of Using SCMs and Blended Cements

Concrete paving mixtures made with SCMs and blended cements have many advantages over concrete made with portland cement alone. Although economic savings are often realized when replacing portland cement with SCMs, shortages of the most desirable SCMs have developed in some markets in recent years, pushing prices of many SCMs upward. Thus, it can no longer be assumed that concrete mixtures containing SCMs will cost less on an initial cost basis. The real economic savings are obtained over the lifecycle, as the enhancements in workability, ultimate strength, and durability often result in improved long-term performance and reduced lifecycle costs.

This is especially true if there is a risk of certain materials-related distresses such as ASR or sulfate attack. In many cases, high-quality SCMs are the only cost-effective means to mitigate harmful deleterious reactions, which is a fact well documented in practice (Taylor et al. 2006, Thomas et al. 2008, ACI 2008). For example, the use of low calcium oxide (CaO) fly ash (CaO < 18 percent) and/or slag cement is recognized as a prescriptive treatment of ASR in the most recent Federal Highway Administration (FHWA) guidelines (Thomas et al. 2008). Guidance in ACI 201.2R shows the effectiveness of using SCMs and/or blended cements to mitigate external sulfate attack (ACI 2008). Guidance on the use of SCMs to prevent ASR is provided in AASHTO PP65-11. It is also well demonstrated that SCMs are extremely effective at reducing the ingress of chloride ions into concrete, reducing the chance of corrosion of embedded steel.

And, finally, SCMs such as fly ash and slag are industrial by-products, meaning they are taken from the waste stream of other industries. By diverting these materials from a landfill and beneficially using them to replace the energy and CO_2-intensive portland cement, significant environmental savings are realized (Van Dam et al. 2012). Combined with better economy and increased longevity, SCM use results in marked improvement in the overall sustainability of a concrete pavement.

Adding SCMs to Concrete

It is common in the US for the concrete supplier to blend portland cement with SCMs at the concrete plant. This requires the use of at least two cement bins. The advantage of this approach is that it is very simple for the concrete producer to alter the replacement level of the SCM batch-to-batch, providing considerable flexibility to serve multiple clients over the course of the year. The addition of a third cement bin provides the opportunity to make ternary blends if filled with another SCM.

The main disadvantage of adding the SCM at the concrete plant is one of control in both the quality of the material and in the amount of SCM added. Concrete suppliers rely almost exclusively on the SCM supplier to ensure the quality of the product. At times, quality can vary significantly enough to have a profound impact on the fresh and/or hardened properties of the concrete, yet still remain within the requirements of the given standard. This is a greater issue for fly ash, which has more variability than slag cement, and can result in unexpected interactions that can affect setting, air content, and strength (Taylor et al. 2006).

Issues regarding control also impact the amount of SCM added to the concrete, either through operator error or equipment failure. This can have serious consequences. For example, too much SCM could result in problems with early strength gain, yet not enough SCM could increase the risk of ASR if the SCM were being used for mitigation.

When the pozzolan, slag cement, and/or limestone are interground or blended by the cement supplier under AASHTO M 240, there is a greater level of quality control over the final product with less potential for unforeseen interactions and incompatibilities (Taylor et al. 2006). In addition, the use of AASHTO M 240 blended cements helps to avoid the potential for proportioning mistakes that can occur in the field. This will enhance batch-to-batch uniformity, providing for more uniformity in the finished pavement. The major drawback, however, is the use of a blended cement limits the concrete supplier's flexibility to adjust the SCM content in response to changing conditions (e.g., cooler weather). As such, the supplier will likely need to have a minimum of three cement silos: one for portland cement, one for an SCM, and another for the blended cement.

Future Trends

From an economic, environmental, and social perspective, the increased use of SCMs is an attractive alternative to the concrete pavement industry, whether batched at the concrete plant or included as part of blended cement. The demands for high-quality SCMs is therefore expected to grow. Yet, there are a number of emerging issues that may restrict the supply of these SCMs in the near future.

The two most common SCMs, fly ash and slag cement, are derived from industrial processes: burning of coal in power plants in the case of fly ash and smelting iron ore in the case of blast furnace slag.

Current trends suggest that coal will slowly be replaced by cleaner-burning and abundant natural gas as the preferred fossil fuel in a number of US power plants. Furthermore, those power plants that continue to burn coal are under pressure to reduce emissions of mercury and sulfur dioxide, either by changing coal sources or by employing technologies that can result in harmful contamination of the fly ash, either through the addition of activated carbon or sodium carbonate/sodium sulfate.

With regard to slag cement, smelting of iron ore is in general decline in the US, negatively affecting supply of molten slag available for granulation.

There is thus some uncertainty that exists regarding the availability of the most highly sought after SCMs in the decade to come. On a positive side, work continues in developing natural pozzolan sources that might be able to fill a void created if industrial by-product SCM supplies dwindle.

Acceptance of limestone cements is growing among agencies, and limestone should remain readily available in the foreseeable future. It is likely that use of ternary mixtures containing limestone combined with another SCM, or combinations of SCMs, will continue to increase because materials can be paired that compensate for each other's side effects yielding a final mixture that has reduced clinker content but performs as required.

Summary

Hydraulic cement concrete continues to be at the heart of transportation infrastructure systems because of its cost effectiveness, ready availability, versatility, and longevity.

While the fundamental ingredient, portland cement, has changed relatively little over time, there is increasing use of supplementary cementitious materials that are used to enhance performance while reducing cost and environmental impact.

This document discusses how these materials influence concrete performance and how they are specified in the US for use in binary and ternary combinations.

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About the National Concrete Pavement Technology Center

The mission of the National Concrete Pavement Technology Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.