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Blended and Performance Cements

This TechBrief provides an overview of blended and performance cements for use in transportation infrastructure. The relatively new labeling for ASTM C595 blended cements, including ternary cements, is described. ASTM C1157 performance cements are also described with particular focus on portland-limestone cements and activated fly ash. An overall summary of the fresh and hardened properties of concrete made with blended and performance cements is also presented, along with a summary of current State practices.

Introduction

Because of its relatively low cost, widespread availability, versatility, and hallmark longevity, portland cement concrete (PCC) is the most widely used building material on the planet, with the equivalent of approximately 1 yd^3 (4,000 lb [1,814 kg]) of concrete used annually for each of Earth's nearly 7 billion inhabitants. In transportation infrastructure alone, concrete is used in a variety of applications, including pavements, foundations, hydraulic structures, bridges, retaining walls, barriers, curbs and gutters, and sidewalks.

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 have significant environmental impacts in terms of energy use, reduction in nonrenewable resources, and greenhouse gas emissions. The latter item receives particular emphasis as it is associated with global climate change, a critical area which is expected to continue 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 while maintaining its economic and social value. One such strategy is to reduce the amount of portland cement used in the concrete, an approach that can be accomplished through the use of chemical admixtures; through mixture proportioning techniques; and by blending supplementary cementitious materials (SCMs) with portland cement (either added by the cement supplier under ASTM C595

[AASHTO M 240] or added by the concrete producer) or through the application of performance cements (such as provided by ASTM C1157) that focus on performance and not cement composition, thereby opening the door for innovative developments.

This TechBrief describes the use of blended and performance cements as one way of increasing the sustainability of concrete mixtures. It first relates cement and concrete production to overall sustainability considerations and then describes the development and use of blended and performance cements as one step in the effort to reduce concrete's carbon footprint and increase its environmental friendliness. It concludes with a look at the fresh and hardened properties of concrete made with blended and performance cements, including a review of current State practices.

Portland Cement, Concrete, and Sustainability

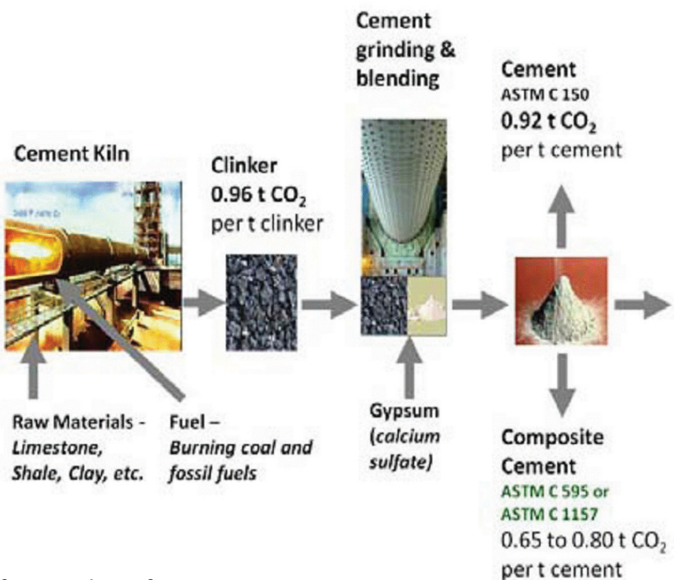
The cement used in typical paving concrete is traditionally portland cement as specified under ASTM C150 or AASHTO M 85. These two specifications have differed in years past, but recent stakeholder efforts resulted in the publication of harmonized standards in 2009 (Tennis and Melander 2010). In addition, SCMs, such as fly ash (obtained from burning coal in power plants and specified under ASTM C618) and slag cement (produced from iron blast furnaces and specified under ASTM C989), are both now routinely used in concrete mixtures to provide economy, improved workability, enhanced long-term strength and durability, and increased sustainability (Van Dam and Taylor 2009).

Globally, portland cement manufacturing produces approximately 5 percent of the world's CO_2 output (PCA 2009). Moreover, portland cement manufacturing is responsible for approximately 95 percent of the CO_2 emissions associated with concrete production and about 85 percent of the energy consumed to produce concrete (Marceau et al. 2007). Thus, one way of reducing the carbon footprint of concrete is to reduce the amount of portland cement that is used, a goal that can be accomplished in a number of ways. As illustrated in figure 1, in the United States about 0.96 t of CO_2 (on average) are associated with the production of 1.0 t of clinker as it exits the cement kiln, while the emissions are reduced to 0.92 t of CO_2 per ton of cement due to intergrinding the clinker with the calcium sulfate (it is the fine grinding of clinker and calcium sulfate that creates the powder that is sold as portland cement). Furthermore, when a composite cement is produced (under ASTM C595 or ASTM C1157), the emissions are reduced to 0.65 to 0.80 t of CO_2 per ton of cement. Figure 1 also provides a table summarizing the positive impact of the addition of SCMs on reduced CO_2 emissions.

ASTM C150 (and AASHTO M 85) allow up to 5 percent high-quality natural limestone to be interground with the clinker, although the practical limit is closer to 3 percent so that loss on ignition requirements can still be met. This intergrinding with limestone further reduces the carbon footprint of portland cement to approximately 0.90 t CO_2 per ton of cement. It was commonly believed that the limestone remains inert, but recent research suggests that most, if not all, of the limestone chemically reacts in a generally positive fashion, reducing porosity and increasing the strength of the hydrated cement paste (Matschei et al. 2007).

Introduction to Modified Hydraulic Cements

Because of their inherent sustainability advantages, there is considerable interest in the uses and applications of modified hydraulic cements for paving concrete, where the term "hydraulic" cement refers to cements (not just portland cements) that undergo chemical reactions with water and will harden underwater. This section briefly describes the characteristics of both blended and performance cements.



Impact of Cement Content and SCMs on CO_2 per Cubic Yard of Concrete

Cementitious lbs/yd^3	% SCM	CO_2 lbs/yd^3
564	0	527
470	0	442
376	0	356
564	25	404
470	25	351
376	25	271
564	50	282
470	50	234
376	50	190

1 lb/yd^3 = 0.59 kg/m^3

FIGURE 1. Amounts of CO_2 produced at various stages of concrete production (based on Roumain and Smartz 2009 and Marceau, Nisbet, and VanGeem 2007).

Blended Hydraulic Cements

When cement manufacturers intergrind or blend portland cement with fly ash or natural pozzolans or slag cement, or create a ternary combination of SCMs, the blended cement is specified under ASTM C595 (AASHTO M 240), Standard Specification for Blended Hydraulic Cements. These materials are classified as follows:

- Type IP(X) to indicate a portland-pozzolan (P) cement in which "X" denotes the targeted percentage of pozzolan expressed as a whole number by mass of the final blended cement. Thus, Type IP(15) is cement that contains 15 percent pozzolan.
- Type IS(X) to indicate a portland-slag (S) cement in which "X" denotes the targeted percentage of slag cement expressed as a whole number by mass of the final blended cement. Thus, Type IS(25) is cement that contains 25 percent slag cement.
- Type IT(AX)(BY) to indicate ternary (T) blended cement in which the "A" refers to the type of SCM (either "P" for pozzolan or "S" for slag cement) that is present in the larger amount by mass and the "B" refers to the SCM (again, either "P" for pozzolan or "S" for slag cement) 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 pozzolan material is listed first, i.e., Type IT(P15)(S15). Two different pozzolans can also be blended together to create a Type IT(PX)(PY).

Typical replacement rates for blended cements are 15 to 25 percent for Type IP and 30 to 50 percent for Type IS. A Type IT might have 15 to 30 percent slag cement and 10 to 20 percent pozzolan, although these can vary significantly depending on the characteristics of the specific SCMs.

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.

- "MH" or "LH" to indicate moderate or low heat of hydration.

Although it has been a more common practice for the concrete supplier to blend cement with SCMs at the concrete plant, when the SCMs are interground or blended by the cement supplier under ASTM C595 (or 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 ASTM C595 (AASHTO M 240) blended cements helps avoid the potential for proportioning mistakes that can occur in the field. However, this does limit the concrete supplier's ability to adjust the SCM content in response to changing conditions (e.g., cooler weather).

Performance Hydraulic Cements

The ASTM C150 (AASHTO M 85) and ASTM C595 (AASHTO M 240) cement specifications discussed thus far are largely prescriptive; that is, they are based on measured chemical and physical properties that are assumed to be related to the performance of the cement in concrete. In contrast, ASTM C1157, Performance Specification for Hydraulic Cement, simply requires that the hydraulic cement meet certain physical performance test requirements, thus focusing on material performance and not material composition. This approach promotes innovative development of composite portland cements (portland cement blended with multiple SCMs and/or limestone) and also opens the door to non-portland-cement hydraulic binders that have the potential to significantly reduce the CO_2 associated with concrete production. Six hydraulic cement types are available under ASTM C1157:

- GU (general use).
- LH (low heat of hydration).
- MH (moderate heat of hydration).
- HE (high early strength).
- MS (moderate sulfate resistance).
- HS (high sulfate resistance).

The two major categories of ASTM C1157 cements being marketed in the United States are portland-limestone cements (PLCs) and activated fly ash cements. These are briefly described in the following sections, along with a short discussion on emerging cement technologies.

Portland-Limestone Cement

PLC is manufactured by intergrinding portland cement clinker with limestone at limestone percentages greater than the 5 percent currently allowed by ASTM C150 (AASHTO M 85). PLC has been used in Europe for over 25 years, where the most popular type contains up to 20 percent limestone, and it has recently been approved for use in Canada (CAC 2009). Canadian PLC contains from 6 to 15 percent limestone and follows the same basic nomenclature as ASTM C1157 cements (GU-L, LH-L, MH-L, and HE-L) except there are currently no provisions for moderate or high sulfate resistance. The 15 percent limit is in place to ensure the PLC performs similarly to conventional portland cement and blended cements. At this replacement level, it is estimated that the use of CSA A30001 PLC reduces CO_2 emissions by up to 10 percent compared to conventional portland cement (CAC 2009).

Although the major motivation to use PLC is to reduce CO_2 emissions, PLC has other advantages. Because limestone is softer than clinker, when the two are interground the resulting limestone particles are finer than the clinker particles, resulting in improved particle distribution and packing. The fine limestone particles also act as dispersed sites on which the formation of hydration products initiates, further densifying the microstructure as hydration proceeds. And, as previously mentioned, the limestone is not chemically inert, but instead reacts with the aluminate phases in portland cement and many SCMs to create carboaluminate phases (Matschei et al. 2007). The net result is that cement manufacturers can optimize the chemical and physical properties of a PLC to achieve equivalent, or even improved, performance to that obtained using conventional portland cement. Several North American field studies have demonstrated that PLC can be used similarly to ASTM C150 and ASTM C595 cements in the construction of concrete pavements (Thomas et al. 2010; Van Dam et al. 2010).

Work is underway at ASTM to transfer PLCs from ASTM C1157 to ASTM C595, with a ballot expected in 2011. A transfer will likely increase the use of PLC in the United States.

Activated Fly Ash

Although PLCs are the most prevalent cement currently specified under ASTM C1157, a number of alternative hydraulic cements are also specifiable under the standard. One such cementitious system is activated fly ash, which consists of a very high volume of coal fly ash (in excess of 90 percent) in which the rate of hydration is controlled through activators and/or retarders.

One example of an activated fly ash product is marketed by CERATECH, Inc., under the Redi-MAX Bulk Cements® label (www.ceratechinc.com). Their products are described as a non-portland, 100 percent non-acid–alkali-activated fly ash. The primary cementing material is Class C fly ash, which is mineralogically and chemically characterized using proprietary means to ensure predictable product performance over a range of fly ash sources and placement temperatures (Hicks et al. 2009). Stated strength gains are impressive, with compressive strengths of 3,000 lbf/in^2 (20.68 MPa) at 6 hours and 10,000 lbf/in^2 (68.95 MPa) at 28 days.

Emerging Technologies

In addition to PLC and activated fly ash, other potential hydraulic cements exist or are emerging. For example, there is considerable interest in a product produced by Calera Corporation (www.calera.com) that purports to be able to sequester CO_2 generated by power plants to form calcium and magnesium carbonates, which in turn may be used as aggregates or possibly as an SCM or cement. Although limited information on the nature of these products is available, at a minimum the resulting carbonates may be suitable for use in PLC to further reduce the carbon footprint of the cement.

Properties of Fresh and Hardened Concrete Made With Blended and Performance Cements

The properties of fresh and hardened concrete made with blended and performance cements are largely controlled by the characteristics of the SCM used in the cement. Table 1 summarizes some of the effects of SCM on these characteristics and other attributes of the concrete.

In general, hydraulic cements blended with Class F fly ash, slag cement, calcined shale, or calcined clay exhibit improved workability, increased setting time, reduced heat of hydration, and reduced bleeding (Taylor et al. 2006). The longer setting times and the reduced heat of hydration can be advantageous during hot-weather concreting, but may be problematic under low placement temperatures. In particular, late season placements with concrete containing Class F fly ash or slag cement can result in slow strength gain, which can hinder timely joint-sawing operations and can also make the concrete vulnerable to freeze–thaw damage. At the same time, the longer setting times and reduced bleeding characteristics of these SCMs may create conditions that will foster plastic shrinkage cracking.

The impact of Class C fly ash on fresh concrete properties is more varied. Although typically water requirements are reduced, workability improved, and bleeding reduced, the effects of Class C fly ash on early setting and heat of hydration can vary greatly depending on the properties of the fly ash. Additionally, the potential for material incompatibilities is increased with a Class C fly ash, which can lead to early setting problems,

TABLE 1. Summary of Effects of Supplementary Cementitious Materials

Property/Characteristic/Attribute	Type F	Type C	Slag Cement
Workability	Improved	Improved	Improved
Setting time	Prolonged	Varies depending on characteristics of ash	Prolonged
Heat of hydration	Reduced	Varies depending on characteristics of ash	Reduced
Bleeding	Reduced	Reduced	Reduced
Air-void system	May adversely affect the establishment of a stable air-void system		
Strength	Slower early strength gain, but long-term strength commonly increased		
Permeability	Reduced	Reduced	Reduced
Resistance to alkali–silica reactivity	Increased	Varies depending on characteristics of ash	Increased

particularly as ambient temperatures increase (Taylor et al. 2006).

One important property often affected by the presence of SCMs is the entrained air-void system that is needed to protect the concrete against freeze–thaw damage. Both the fineness of the SCM and the nature of carbon it contains can negatively impact the ability to create a suitable air-void system in the concrete. Most SCMs will require additional air-entraining admixture to achieve target air contents. In the case of fly ash, particularly Class F fly ash, the higher carbon content can result in a collapse of the air-void system. This issue has become more relevant as activated carbon, which is being used to mitigate mercury emissions at power plants, is at times commingled with the fly ash and requires beneficiation to remove it.

The two major physical properties of hardened concrete made with blended and performance cements containing SCMs are strength gain and permeability. Although early strength gain is often delayed by most SCMs, long-term strength is commonly increased. This positive attribute is a result of the improved microstructure resulting from pozzolanic and supplementary hydraulic reactions, which creates more desirable hydration products while reducing permeability.

Blended and performance cements can be specifically selected to address alkali–silica reactivity (ASR) and sulfate attack. The effectiveness of the blended or performance cement to mitigate ASR is an optional requirement at the purchaser's request and is based on the expansion results from ASTM C227, Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method). In addition, ASTM C1567, Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method), can be used to determine the effectiveness of the cementitious materials in mitigating ASR (Thomas et al. 2008).

Resistance to sulfate attack is another optional requirement at the purchaser's request for both ASTM C595 and C1157 cements. In both cases, cement can be designated as having moderate or high sulfate resistance based on the expansion results from ASTM C1012, Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution.

Cement Applications and State Highway Agency Practices

Table 2 summarizes general applications for hydraulic cements for general concrete construction. Obviously, the use of ASTM C150 cements is well established, but it is interesting to note that ASTM C595 (AASHTO M 240) blended cements are broadly accepted by highway agencies throughout the country and have been effectively used for decades. ASTM C1157 cements, on the other hand, are approved by only a few State highway agencies, including in Colorado, Utah, and New Mexico, but use is expected to increase in response to a worldwide growing interest in sustainability. Major barriers to acceptance of ASTM C1157 include 1) lack of an equivalent AASHTO specification, 2) lack of experience working with these cements, and 3) uncertainty regarding the long-term durability of concrete made with ASTM C1157 cement.

Summary

State highway agencies are being confronted with the task of reducing the environmental footprint of transportation infrastructure, with particular emphasis being placed on reducing emissions such as CO_2. The manufacturing of portland cement clinker, the principal binder in concrete, produces nearly 1 t of CO_2 emissions for each ton of clinker. Consequently, any strategy that can be used to effectively reduce the amount of portland cement clinker in concrete can have significant sustainability advantages, provided that constructability and performance can be maintained. The use of ASTM C595 blended cement and ASTM C1157 performance cement are two proven strategies that can be employed to reduce the carbon footprint of concrete by up to 50 percent without compromising performance. Blended cement is commonly used in the transportation sector, but only a few agencies are currently using performance cements. Although the motivation to use these cements will continue, one major barrier to their more widespread implementation is the need to develop a better understanding of factors that contribute to their successful use in constructing good-performing concrete pavements. As research continues, it is expected that their overall acceptance will increase, thus enabling them to significantly contribute to the construction of sustainable transportation infrastructure.

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TABLE 2. Applications for Hydraulic Cements (Tennis and Melander 2010; © 2010 American Concrete Institute. Reprinted by permission.)

Cement Specification*	General Purpose	Moderate Heat of Hydration	High Early Strength	Low Heat of Hydration	Moderate Sulfate Resistance	High Sulfate Resistance
ASTM C150 Portland Cements	I	II(MH)	III	IV	II, II(MH)	V
ASTM C595 Blended Hydraulic Cements	IS(<70) IP IT(P<S<70) IT(P≥S)	IS(<70)(MH) IP(MH) IT(P<S<70)(MH) IT(P≥S)(MH)	—	IP(LH) IT(P≥S)(LH)	IS(<70)(MS) IP(MS) IT(P<S<70)(MS) IT(P≥S)(MS)	IS(<70)(HS) IP(HS) IT(P<S<70)(HS) IT(P≥S)(HS)
ASTM C1157 Performance Hydraulic Cements	GU	MH	HE	LH	MS	HS

*Check the local availability of specific cements as all cement types are not available everywhere.

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