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BLENDED CEMENTS FOR NEXT GENERATION PAVING

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Introduction

State highway agencies (SHAs) have long relied on concrete mixtures based on portland cement that meet the requirements of AASHTO M 85 (ASTM C150/C150M) Standard Specification for Portland Cement. Modern-day portland cement is very similar to the portland cement patented by Joseph Aspdin in 1824, but important changes have been necessitated by the cement performance demands of the modern concrete industry. For portland cements, these changes include an increased alite to belite ratio to achieve higher early strength, higher fineness, and the use of organic and inorganic processing additions to improve production efficiencies.

Approaches to producing blended cements have also been developed, where portland cement is the major ingredient and materials such as limestone, slag cement, and pozzolans are included at the point of cement production, either by blending the materials or by intergrinding the blended components with clinker. Blended cements have not been widespread until recently, but for a number of reasons that will be discussed, these cements are becoming common.

The demand to reduce the global warming potential (GWP) of portland cement concrete has led to a rapid increase in the production and use of blended cements. The production of cement clinker is the most significant contributor to the GWP of portland or blended cement, accounting for approximately 90% of the CO_2 emissions associated with portland cement production (Lehne and Preston 2018). Therefore, reducing the amount of clinker in a unit volume of any cement leads to a direct reduction in the GWP of that cement and, in turn, a reduction in the GWP of concrete. Blended cement is a means to reduce the clinker content of concrete while achieving the required concrete performance.

In the immediate future, blended cements will significantly increase in use, and a return to the use of straight portland cement will, for all practical purposes, not be realistic. The purpose of this technical brief is to introduce the blended cement concept and discuss the types of blends that can be anticipated as the industry moves forward. Achieving industry carbon reduction goals will require significant changes in how concrete is proportioned and used and will necessarily involve increased use of blended cements. In the near term, most blended cements will be based on conventional materials that the industry is already familiar with (e.g., clinker, portland cement, limestone, coal fly ash, natural pozzolans, and slag), and the transition to blended cements based on these materials will be a logical first step. Other new blends will follow, such as cements based on clinker, limestone, and calcined clay (LC^3) and blends that rely more heavily on slag cement. Changes are inevitable if the cement and concrete industry is to achieve its goal of carbon neutrality by 2050, and blended cements will be a key tool for achieving that goal.

History of Blended Cements

Production and Use

The use of blended cements in North America can be traced back to as early as 1900, when the US Army Corps of Engineers investigated blends of portland and slag cement (Mather 1957). The research on portland and slag cement blends conducted at the time reported good performance for sea water exposure and for use in mass concrete placement. However, such blends were not commercially available and did not come to market until the 1950s. As an example of the limited production in this era, as late as 1994 only one plant in the United States was producing a blended cement, which was an AASHTO M 240 (ASTM C595/C595M) Type IP(20). That plant started producing this blended product in 1972, and its output ranged from 45,000 mt to 180,000 mt (50,000 to 200,000 tn) annually between 1972 and 1995 (Malhotra and Hemmings 1995). Until that same period, no fly ash or slag blended cement had been produced in Canada (Malhotra and Hemmings 1995).

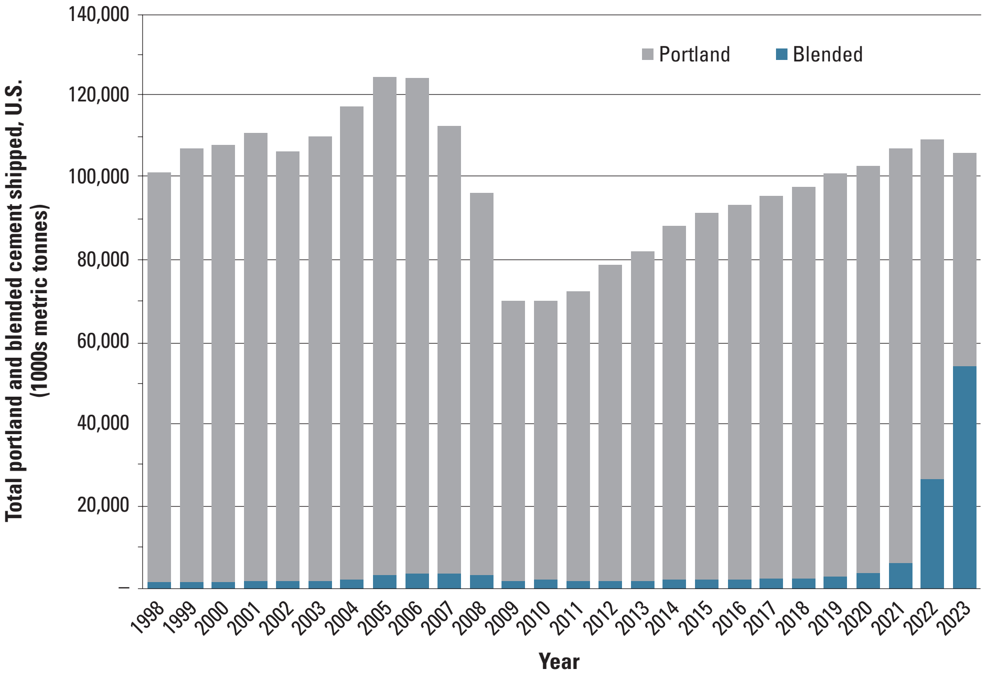
Data from the United States Geological Survey (USGS) show that shipments of blended cement were negligible (i.e., less than 5% of total shipments) until 2021, when the use of blended cement began to increase significantly. It is estimated that over 50% of all cement shipped in the United States in 2023 was a blended cement (Figure 1). Regarding the blended cement shipped in 2023, it is estimated that over 97% was AASHTO M 240 (ASTM C595) Type IL (USGS 2024).

Blended Cement Specifications

Though interest in the use of blended cement dates back to the early 1900s, standard specifications were not adopted until the 1950s. At that time, a series of standard specifications were adopted for blended products, including ASTM C 205-58T Standard Specification for Portland Blast-Furnace Cement; ASTM C 340-58T Standard Specification for Portland Pozzolan Cement; and ASTM C 358-58 Standard Specification for Slag Cement. ASTM C 340-58T focused primarily on blends including natural pozzolans and "some fly ashes," while blends of slag cement and lime were permitted under ASTM C 358-58.

In 1967, the first version of ASTM C595 was published as ASTM C 595-67 T Tentative Specification for Blended Hydraulic Cements. ASTM C 595-67 T covered three types of blended hydraulic cements, essentially incorporating the requirements of ASTM C 205, C 340, and C 358 into one standard. The types identified were portland blast furnace slag cement, portland-pozzolan cement, and slag cement.

Portland blast furnace slag cement was assigned the designation Type IS, which limited the blast furnace slag constituent to 25% to 65% by mass of the total blend.



Data source: USGS Mineral Industry Surveys

Figure 1. Estimated shipments of portland cement and blended cement manufactured in the United States using domestic and imported clinker and cement from 1998 to 2023

This early standard did recognize that such blends could improve the sulfate resistance of concrete and reduce the rate of heat evolution from mass concrete and therefore included a moderate sulfate resistance (MS) and moderate heat of hydration (MH) designation. Type IS(MS) blends had a slightly reduced 3- and 7-day strength requirement; 28-day strength requirements were the same for both IS and IS(MS). The MS designation also limited the portland cement tricalcium aluminate (C_3A) to 8.0% maximum. Type IS(MH) cements were required to meet 7- and 28-day heat of hydration requirements, unlike normal Type IS cements, and were only required to meet 80% of the stated strength requirements for a Type IS cement at all specified ages. Only Type IS blends could qualify with the MS or MH designation.

Portland-pozzolan cement had two general designations: Type IP and Type P. Type IP covered blends of portland cement and pozzolan, with the pozzolan limited to 15% to 40% by mass of the blend. A pozzolan to be used as a blended constituent was required to meet a loss on ignition (LOI) requirement, a maximum fineness requirement of 14% retained on a 325 mesh sieve, and a minimum strength of 5.5 MPa (800 psi) using a lime-pozzolanic activity test that required a 7-day elevated-temperature curing procedure. The Type P designation was for blends for use where "high strengths at early ages are not required." This type had no 3-day strength requirement and a lower 7- and 28-day strength requirement.

The last blend addressed in this first version of the specification was slag cement, which was a blend of ground granulated blast furnace slag and lime where the slag constituent was at least 60% by mass of the total blend. These blends were identified as Type S and had the lowest strength requirements, approximately half those of the other blends at 28-days. Type S blends were also the only blends having no fineness requirements.

For all types identified in this specification, there was a companion air-entraining blend identified by appending an "A" to the type designation.

In the mid-1970s, two more types were added: a pozzolan-modified portland cement blend, Type I(PM), and a slag-modified portland cement, Type I(SM). Both of these covered blends where the blended constituent (i.e., pozzolan or slag) was used in quantities less than the minimum required by Type IP, Type P, or Type IS. Adding these additional types, along with the associated air-entraining versions, made the standard unwieldly and confusing.

In 2006, Specification C595 was revised significantly and took on its current naming conventions. The 2006 version had two types: Type IS portland blast furnace slag cement and Type IP portland-pozzolan cement. Type S, Type I(PM), and Type I(SM) were dropped. The new ASTM C595 naming conventions greatly simplified the identification of blends. The type was appended with (X), where X is the targeted percentage of slag or pozzolan in the blend. Other modifiers to the type designation were (A) for air-entraining, (MS) for moderate sulfate resistance, (MH) for moderate heat of hydration, and a new designation added for low heat of hydration (LH).

In 2007, the high sulfate resistance (HS) designation was added along with the associated requirements throughout the standard. In 2009, a new type, Type IT, was added for ternary blends, which are combinations of portland cement and two different blending constituents. The naming practice was expanded for ternary blends to use the form Type IT(AX)(BY), where A is either "S" or "P" for the predominant blending constituent (i.e., slag or pozzolan), X is the targeted percentage of constituent A, B is the minor blending constituent, and Y is the targeted percentage of constituent B. Also in 2009, ASTM C595/C595M was published, which is the dual-units version of the standard in use today. The most recent type added to ASTM C595 was Type IL for portland limestone cement, added in 2012. This new type allowed for the addition of 5% to 15% ground limestone as a blended constituent to produce a binary blended cement, or as one of the two blended constituents in a ternary blended cement. It should be noted that ASTM C595 allows for blending to be performed as a separate operation or for materials to be blended by intergrinding with clinker and gypsum; limestone is most commonly interground in US production. Another significant change occurred in 2014, when requirements for silica fume were included in the pozzolan requirements, permitting use of silica fume as a blending constituent.

The current combinations of materials that can be blended under ASTM C595 are shown in Table 1.

In 1973, the American Association of State Highway and Transportation Officials (AASHTO) adopted AASHTO M 240 Standard Specification for Blended Hydraulic Cement and in 2013 adopted the dual-units version AASHTO M 240M/M240 (AASHTO 2024). For the past 15 years, AASHTO and ASTM have worked to harmonize these two standards, and as of today they are fully harmonized apart from some minor editorial differences. In moving toward the stated industry carbon reduction goals, AASHTO M 240 (ASTM C595) will be an increasingly common cement specification, and SHA engineers, concrete producers, and contractors will need to become as familiar with the specification as they are with the portland cement specifications.

Table 1. Summary of constituent limits for blends specified in AASHTO M 240 (ASTM C595-24)

Type	Blended Constituents			Hydrated Lime[1]
	Slag	Pozzolan	Limestone	
IS	$S \leq 95$	0	$L \leq 5$	If $S \geq 70$, hydrated lime may be used
IP	0	$P \leq 40$	$L \leq 5$	—
IL	0	0	$5 < L \leq 15$	—
IT ($P+L+S < 70$)	$S < 70$	$P \leq 40$	$L \leq 15$	—
IT ($S \geq 70$)	$S \geq 70$	$P \leq 40$	$L \leq 15$	Hydrated lime may be used

S = slag cement, P = pozzolan, L = limestone

[1] Lime may be used in some blends as shown, but this is not common and is a carryover from the original slag cement specification. The lime is not counted as a blended constituent as is slag, pozzolan, or limestone. The amount of lime is not limited directly but is practically limited by the LOI requirements of the specification.

Another specification that can play a significant role in the adoption of blended cements is ASTM C1157/C1157M Standard Performance Specification for Hydraulic Cements. This standard was originally approved in 1992 but has not been widely adopted to date for a variety of reasons. It has, however, been used as a vehicle to introduce new blended cements. Of note, early field demonstrations of AASHTO M 240 (ASTM C595/C595M) Type IL cement for paving were performed in Colorado and Utah, and that portland-limestone cement was specified as an ASTM C1157 cement (Van Dam and Smartz 2010, Van Dam et al. 2010). In essence, ASTM C1157 provides the same information found in AASHTO M 85 (ASTM C150) but with some notable changes. The standard physical requirements of comparable cement types under each specification are similar, but in the case of ASTM C1157, requirements such as heat of hydration and sulfate resistance are standard requirements for the applicable cement type; for AASHTO M 85 (ASTM C150) cements, these characteristics are optional requirements. The strength requirements for ASTM C1157 cements are also slightly higher than those for comparable ASTM C150 cement types. However, from a practical perspective, both cements are required to provide the same physical performance.

The major objection expressed regarding ASTM C1157 cements is that no requirements are provided for the chemical composition. An AASHTO M 85 (ASTM C150) cement does need to meet limited chemical requirements, depending on the type of portland cement, and for cement produced in a single plant, composition can be an important part of the quality assurance process. However, as will be discussed, the composition is much less meaningful when cements produced in separate facilities are compared, and physical performance requirements become the key measure.

Comparison of Specifications

Regarding the composition of an ASTM C1157 cement, it should first be noted that reporting the constituents is required upon request of the purchaser. The specification states, “At the request of the purchaser in the contract or order, the manufacturer shall state in writing the types and amounts of the ingredients used in manufacture of the hydraulic cement.” Further, the specification states that the cement shall be analyzed for information purposes and the results are to be reported with the manufacturer’s certificate. In contrast, a Type I cement under AASHTO M 85 (ASTM C150) needs to limit and report the magnesium oxide (MgO), LOI, insoluble residue, and equivalent alkali content. (Note that equivalent alkali content is expressed as $Na_2O + 0.658\ K_2O$, where Na_2O is sodium oxide and K_2O is potassium oxide.) Sulfur trioxide (SO_3) is also reported, but the limit can be exceeded by demonstrating performance using ASTM C1038/1038M Standard Test Method for Expansion of Hydraulic Cement Mortar Bars Stored in Water. ASTM C1157 does not limit the SO_3 content but does require the same ASTM C1038 performance testing permitted in AASHTO M 85 (ASTM C150) for all cements, regardless of the sulfate content.

If the comparison to AASHTO M 85 (ASTM C150) cements is expanded to include Type II, or more commonly Type I/II, the manufacturer needs to limit and report alumina (Al_2O_3) and iron oxide content (Fe_2O_3), although the limit on Fe_2O_3 does not apply if the optional sulfate resistance performance testing is specified. The manufacturer also needs to limit and report the calcium aluminate (C_3A) content, but the C_3A is not directly measured. It is calculated using the Bogue equation (Bogue 1929, Bogue 1955) based on the cement bulk alumina (Al_2O_3), silica (SiO_2), calcium oxide (CaO), and iron oxide (Fe_2O_3) contents. Reporting CaO and SiO_2, arguably the two most important oxides, is not required by the specification, but many SHAs require this, and the test results for these analytes are routinely reported by manufacturers along with the full results of the Bogue calculations.

When examining the requirements of the current AASHTO M 85 (ASTM C150) specifications, it is clear that limited compositional prescription is required for general use cements. Further, the optional requirements that are routinely tested by the manufacturer, even when not requested, align very closely with the requirements of ASTM C1157. In the end, it is physical performance that establishes whether any cement meets the demands of the concrete structural design. In design, the construction industry does not rely on the composition of the cement but rather on knowing that it will perform like a portland cement. As the industry moves toward blended cements, which is happening rapidly, specifiers will not be able to rely on compositional prescription and will necessarily rely more on performance measures.

In comparing all of the cement specifications discussed here, the blended cement specification AASHTO M 240 (ASTM C595) falls between the two extremes of the current portland cement specifications and the performance-based specification. The blended cement specification provides a limited chemical prescription similar to that found in AASHTO M 85 (ASTM C150), such as the prescription to limit and report MgO, LOI, insoluble residue, and SO_3, although the SO_3 limit can be exceeded by demonstrating performance using ASTM C1038/C1038M, just like in the other cement specifications. However, the constituents of an AASHTO M 240 (ASTM C595) blend are not limited to clinker predominantly, as is the case with portland cement. In this sense, the AASHTO M 240 (ASTM C595) specification is similar to the performance-based specification. The difference is that the blended cement specification puts limits on what can be blended and what the possible fraction of each component can be. The AASHTO M 240 (ASTM C595) specification also employs a clear naming convention that conveys the targeted mixture.

In summary, AASHTO M 240 (ASTM C595) provides the certainty of the age-old portland cement standards but the opportunity to use materials other than clinker, thereby reducing the GWP of the cement and concrete. Given the limits included in AASHTO M 240 (ASTM C595), some blends will need to be specified under the performance-based specification, but it is expected that AASHTO M 240 (ASTM C595) will evolve further and embrace the other new blends that are emerging.

Blended Cement Constituents for AASHTO M 240 (ASTM C595)

The following sections briefly discuss the constituents allowed in AASHTO M 240 (ASTM C595) blended cements.

Slag

When comprising less than 25% of the blend (i.e., Type IS(<25) or Type IT(S<25)), slag must meet a fineness requirement of 20.0% maximum retained on a 325 mesh (45 micron) sieve and must also meet an activity index requirement of 75.0 minimum. The slag cement tested for strength activity must have the same fineness that is believed to be present in the finished cement. Most manufacturers use ground slag cement, so the fineness is known. When necessary, however, the granulated blast furnace slag is ground in the laboratory to meet this requirement before strength testing is performed. An activity index test mixture for slag uses 70% by volume slag and 30% by volume portland cement. The amount of mixing water used is that required to attain a flow of 100 to 115, the same flow as a 100% portland cement control mixture.

The test and control specimens are cured in the molds in a moist room at a temperature of 23°C (73.5°F) for 20 to 24 hours and then removed from the molds, placed in sealed containers, and cured at 38°C (100°F) for 27 additional days. The average compressive strength of the test samples is determined at 28 days and reported as a percentage of the average compressive strength of control samples cured under the same conditions and tested at 28 days of age. This percentage is referred to as the activity index. There are no additional requirements for the slag component of a Type IS or Type IT blended cement; a slag cement used in a blended cement is not required to meet AASHTO M 302 (ASTM C989/C989M).

Pozzolan

To be included as a pozzolan in a blended cement, a material needs to meet the activity index and fineness requirements of the specification. AASHTO M 240 (ASTM C595) does not reference any other specifications for pozzolans. However, if the pozzolan is a natural pozzolan, coal ash, or silica fume, it is required to meet an LOI requirement of 10% for a natural pozzolan and 6% for coal ash and silica fume. For all pozzolans, the fineness requirement is 20.0% maximum retained on a 325 mesh (45 micron) sieve. The activity index requirement is 75.0 minimum, the same as that of slag and obtained using the same test procedure, which includes pregrinding when necessary. For a pozzolan, the activity test mixture is 35% by volume pozzolan and 65% by volume portland cement. There are no additional requirements for the pozzolan component of a Type IP or Type IT blended cement.

Limestone

Limestone for use in a blended cement was, until recently, limited to "naturally occurring" materials meeting the definition of limestone provided in ASTM C51 Standard Terminology Relating to Lime and Limestone (As Used by the Industry). This standard defines limestone as "a sedimentary rock consisting primarily of calcium and magnesium carbonates." It suggests three classes of limestone based not on the calcite ($CaCO_3$) content but rather the magnesite ($MgCO_3$) content: dolomitic ($MgCO_3$ 35% to 46%), magnesian ($MgCO_3$ 5% to 35%), and high-calcium ($MgCO_3$ 0% to 5%). In AASHTO M 240 (ASTM C595), the additional requirement of carbonate content equal to or greater than 70% is used, with a minimum $CaCO_3$ of 40%. The $CaCO_3$ content is not directly determined but rather is based on the bulk CaO content. This definition of limestone has existed since the introduction of Type IL cement in 2012 and follows from the historic definitions used for limestone in the manufacture of portland cement.

Recently, changes have been made to AASHTO M 240 (ASTM C595), as well as AASHTO M 85 (ASTM C150), to allow for the use of manufactured forms of calcium carbonate. To accommodate manufactured forms of calcium carbonate, the definition of limestone in AASHTO M 240 (ASTM C595) was changed to the following: "either limestone, as defined in Terminology C51, or manufactured mineral forms of calcium carbonate for use in blended cements." The requirement of 70% minimum carbonate was retained.

As the industry moves to achieve net zero carbon by 2050, various forms of carbon capture and sequestration will be developed and will inevitably produce, in most cases, relatively high-purity $CaCO_3$. Allowing for this material to be used in portland cement or Type IL blended cement provides the opportunity to sequester process-generated CO_2 in the cement and reduce the amount of raw material used. An added advantage is that manufactured calcium carbonate can be reactive in some cases and contribute to strength development rather than simply serving as a mineral filler (Hargis et al. 2021, Yaqiang et al. 2023).

Hydrated Lime

Hydrated lime is sometimes used in high-slag blends to accelerate the slag hydration reaction. The lime must meet the requirements of ASTM C821 Standard Specification for Lime for Use with Pozzolans, except that when interground in the cement production process, there is no minimum fineness requirement. There is no minimum requirement or limit on the amount of lime in a blended cement, but the amount used is limited in practice by the overall LOI requirement for the final blend.

Evolution of Blended Cements

In response to a demand for cements with a GWP lower than that of portland cement, new blended cements are being introduced. In addition to new hydraulic blended cements, other alternative cements are emerging that are comprised of no portland cement clinker. No-clinker cements, however, are currently niche products. At present, producers commonly seek to specify these cements under ASTM C1157, although some are not hydraulic cements and therefore do not fall under the scope of ASTM C1157. To provide a more appropriate approach, a new standard specification is under development at ASTM International to cover nonhydraulic cements. The approach to this new specification will be performance based.

Examples of how blended cements are evolving are discussed in this section. For the purposes of this technical brief, only cements with some fraction of portland cement are discussed.

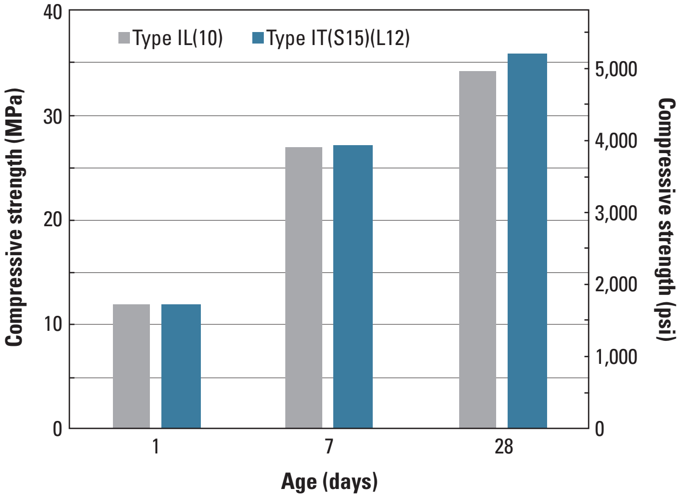
AASHTO M 240 (ASTM C595) Type IT

Historically, standard specifications for blended cements have been for binary blends such as Type IP (portland cement plus a pozzolan) or Type IS (portland cement plus slag). Ternary mixtures specified as Type IT have been part of the specifications for the past 15 years but have not been broadly embraced by specifiers. However, this is changing, and as the construction industry moves toward carbon reduction goals, ternary blends will become more common. This is partially driven by the need in some markets to extend limited supplies of either pozzolan, slag, or both but is also driven by the demonstrated performance benefits of these blends, along with the promise of significant reductions in GWP.

Research has shown that combining two supplementary cementitious materials (SCMs) can provide synergies where the positive aspects of one SCM can balance out the shortcomings of another (Hooton et al. 2018, Thomas et al. 2010). To illustrate, consider a blend of silica fume and Class F fly ash. The silica fume contributes more to early-age strength and less to strength at later ages. The fly ash performs in the opposite manner, contributing little to early-age strength but significantly improving later-age strength. The blend of these SCMs performs better than either material separately, and that increased performance allows for higher replacement levels of portland cement and greater carbon reduction without sacrificing other performance aspects. For example, a commercially available ternary blend of portland cement, 3% to 5% silica fume, and 20% to 25% slag, was shown to provide strengths similar to those of portland cement alone while significantly reducing permeability and mitigating alkali-silica reactivity (ASR), as demonstrated using ASTM C1293/C1293M (Thomas et al. 2007). Similar scenarios can be identified with numerous combinations of SCMs.

Ternary mixtures can also comprise limestone and an SCM, although such blends have not been common. However, Type IL blended cement is commonly combined with SCMs at the ready mix plant to improve performance. In a study for the Indiana Department of Transportation, a Type IL blended cement with 20% Class C fly ash showed a 7% average increase in 7-day flexural strength compared to the same concrete mixture prepared using an AASHTO M 85 (ASTM C150) Type I/II cement with no SCM replacement (Barrett et al. 2013). Other researchers have reported similar performance improvements for Type IL blended cement combined with Class C fly ash, slag, and, to a lesser extent, Class F fly ash (Cost et al. 2013).

The production of hydraulic blended cements is increasing and provides users with reduced-GWP cements that have performance comparable to AASHTO M 85 (ASTM C150) Type I/II cements or AASHTO M 240 (ASTM C595) Type IL cements. Providing a blended product helps smaller concrete production facilities that may have limited silo space implement reduced-carbon cements. It also allows for optimization of the particle size distribution of the cement constituents and proper sulfate balance to minimize potential admixture interactions. For example, a ternary blend was introduced in 2024 in some midwestern states and has been approved by the Michigan and New York State Departments of Transportation. The blend is an AASHTO M 240 (ASTM C595) Type IT(S15)(L12). Figure 2 shows concrete trial batch data comparing the compressive strength of mixtures prepared using a Type IL(10) blended cement with a Type IT(S15)(L12) blended cement. The mixture design used a total cementitious content of 300 kg/m³ (505 lb/yd³) and a water-to-cementitious materials (w/cm) ratio of 0.56. In terms of compressive strength, the two blended cements are similar.



Data source: USGS Mineral Industry Surveys

Figure 2. Concrete trial batch data comparing mixtures prepared using a Type IL(10) blended cement with a Type IT(S15)(L12) blended cement

With respect to cradle-to-gate GWP, the Type IL cement has a GWP of 795.5 kg CO_2 eq/t of cement while the Type IT(S15)(L12) cement has a validated GWP of 668.1 kg CO_2 eq/t of cement, an approximate 16% reduction (NRMCA 2024a). Compared to the GWP for an AASHTO M 85 (ASTM C150) Type I/II cement from the same plant, which is 876.6 kg CO_2 eq/t of cement, the Type IT(S15)(L12) cement provides a GWP reduction of nearly 24% (NRMCA 2024a).

One point of discussion regarding blended cements centers on where the blending should occur. Historically, concrete producers have purchased cement and blending constituents separately, stored those materials in silos at the batch plant, and produced concrete mixtures using various combinations of materials in response to customer specifications. For many ready mix concrete producers, this leads to thousands of mixture designs to keep on record, and although this approach clearly provides the maximum flexibility in mixture design at the ready mix plant, it raises the question, Are all of those different mixture designs really needed? As the industry moves into an era of environmental product declarations (EPDs) for every mixture, is it practical to maintain duplicative mixture designs?

Sourcing individual constituents can also lead to mixture variability caused by variations in the properties of the blending constituents or the cement, and some smaller producers could benefit from this work being shifted to the cement producer. In some cases, adverse interactions can occur between constituents or with the admixtures used in the concrete. Producing a blended product as a manufactured product allows for quality control of the blend and minimizes incompatibility issues. Specifically, the sulfate balance of the mixture can be adjusted to match the requirements of the specific blend as well as the fineness.

There is not necessarily a clear answer to the question of where to blend, and likely both approaches will be used depending on the type of concrete manufacturing facility considered. In the case of concrete paving, where a portable batch plant is deployed at the construction site, a blended cement offers the simplicity of maintaining one silo for cementitious materials.

Because most cement producers are increasing production of Type IL blended cements and decreasing production of Type I portland cement, it will be desirable to produce ternary blended hydraulic cements meeting AASHTO M 240 (ASTM C595) Type IT that use Type IL as the base cement rather than AASHTO M 85 (ASTM C150) Type I.

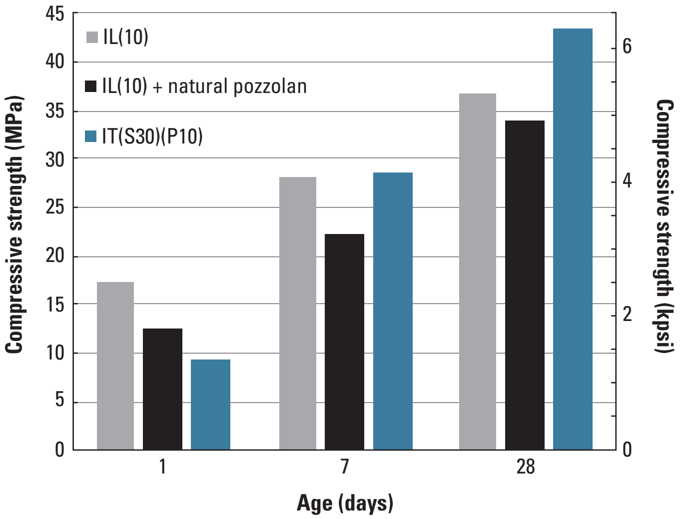
Blends based on Type IL cements perform well, taking advantage of the known benefits of combining limestone and SCMs in blended cements. Currently, AASHTO M 240 (ASTM C595) does not permit more than two blending constituents, and the limestone is counted as one of those constituents. In this regard, note that concrete producers that have two SCMs in inventory and use those SCMs in a mixture design with a Type IL blended cement are technically not providing ternary blends.

In anticipation of this transition to ternary blends based on Type IL cement, both AASHTO and ASTM International are considering changes to their specifications to allow for blending portland cement with up to 15% limestone, including the limestone present in the base cement, and more than one pozzolan or slag. Currently, this type of blend can only be specified under ASTM C1157, but committees within both AASHTO and ASTM International feel that this type of blend should be addressed under AASHTO M 240 (ASTM C595).

Blended cements using four components (i.e., portland cement, limestone, slag, and pozzolan) are currently being produced. One example is an ASTM C1157 Type GU cement that has been approved for use in Nebraska and Iowa by their respective SHAs. The blend consists of an AASHTO M 240 (ASTM C595) Type IL(10) cement plus 30% slag and 10% natural pozzolan. This results in a final blend of portland cement, 6% limestone, 30% slag, and 10% natural pozzolan. Although technically this is a four-component blend, the SHAs have designated it as a Type IT(S30)(P10). It has been used extensively in those states and elsewhere with excellent results. The Nebraska Department of Transportation (NDOT) requires all cements to be blended, and for NDOT projects, no SCMs are added at the point of concrete production. Given the need for ASR mitigation in many parts of the state, a blend must be able to mitigate ASR in addition to meeting other physical requirements. Example performance data using this blended cement are presented in Figure 3 and Figure 4.

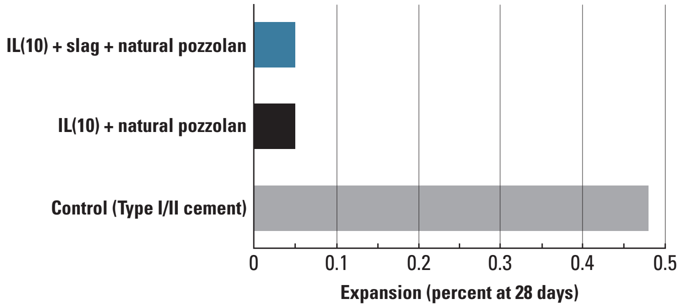
For the results shown in Figure 3, concrete mixtures were prepared using a fixed w/cm ratio and total cementitious content across all mixtures. The concrete mixtures were prepared using (1) Type IL(10) blended cement only; (2) a blended limestone-pozzolan cement comprising Type IL(10) blended cement and a 25% replacement of natural pozzolan, resulting in a final blend of portland cement, 8% limestone, and 10% natural pozzolan; and (3) a ternary blended cement comprising Type IL(10) plus 30% slag cement and 10% natural pozzolan, resulting in a final blend of portland cement, 6% limestone, 30% slag cement, and 10% natural pozzolan. In Figure 3, the ternary blended cement mixture shows a lower 1-day strength, which is common with slag-based blended cements. At 7-days and beyond, however, the ternary cement performed as well as the Type IL blend alone.

Figure 4 shows the results of ASR testing using ASTM C1567 Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method).



Unpublished data courtesy of J. Clendenen, Holcim

Figure 3. Compressive strengths of three concrete mixtures: a control mixture comprised of Type IL(10) blended cement only, a blended limestone-pozzolan mixture, and a ternary blended Type IT(S30)(P10) mixture



Unpublished data courtesy of J. Clendenen, Holcim

Figure 4. Results from ASTM C1567 testing for three mixtures: a control mixture prepared using Type I/II portland cement only, a blended limestone-pozzolan mixture, and a ternary blended Type IT(S30)(P10) mixture

The control mixture was prepared using Type I/II portland cement only. The test mortar mixtures were prepared using the blended limestone-pozzolan mixture comprising Type IL(10) blended cement and a 25% replacement of natural pozzolan, resulting in a final blend of portland cement, 8% limestone, and 10% natural pozzolan, and the ternary blended mixture comprising Type IL(10) blended cement plus 30% slag cement and 10% natural pozzolan, resulting in a final blend of portland cement, 6% limestone, 30% slag cement, and 10% natural pozzolan. The results indicated that both the blended limestone-pozzolan cement and the ternary blended cement demonstrated ASR mitigation. The control sample was tested in accordance with AASHTO T 303 (ASTM C1260) Standard Method of Test for Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction using the same aggregate and a Type I/II portland cement. Note that both the AASHTO T 303 (ASTM C1260) and the ASTM C1567 tests were conducted out to 28 days in accordance with NDOT testing requirements.

In addition to meeting physical performance requirements, the example ternary blend also meets carbon reduction goals. The baseline Type IL(10) blended cement has a GWP of 724 kg CO_2 eq/t, and the blended limestone-pozzolan cement has a verified GWP of 608 kg CO_2 eq/t (Holcim 2021). In comparison, the ASTM C1157 Type GU has an estimated GWP of 553 kg CO_2 eq/t; a third-party-verified EPD for this blended cement is under development.

Limestone Calcined Clay Cement (LC^3)

Blended hydraulic cements allow slag or pozzolans as the SCM constituent, either separately or in combination in a ternary blend. Research on Type IL cements has shown that ground limestone will react with C_3A phases in cement to form various forms of carbo-aluminates (Tennis et al. 2024). Technically, however, limestone is not considered to be an SCM. Limestone has been shown to react with cement phases when added in amounts of 5% by mass or less (Matschei et al. 2006, Lothenbach et al. 2008). Beyond that replacement level, limestone blended with only a portland cement is documented to further contribute to strength by providing nucleation sites for hydration products and by serving as a fine-particle mineral filler (Tennis et al. 2024). Further research has shown that this “filler effect” does not result from the limestone providing surfaces for nucleation products, but rather the filler contributes by improving particle packing and reducing the interparticle distance between cementitious particles (Berodier and Scrivener 2014).

As industry expands the production and use of hydraulic blended cements, there will be an increased demand for SCMs. Unfortunately, SCM supplies are challenged. The most commonly used SCM in the United States is coal ash, specifically coal fly ash. Coal fly ash results from the combustion of coal to produce electricity, but in response to the same dynamics driving cement to become carbon neutral, coal-fired power plants are either being shuttered or converted to natural gas fuel sources to achieve carbon reduction goals in the power generation sector. The result is a dramatic reduction in the production of coal fly ash. The most recent records show that from the peak production of over 65 mt (72 million tn) in 2008, coal ash production has decreased by over 61% (ACAA 2009, ACAA 2023) as of 2022. Interestingly, the use of coal fly ash in concrete has also dropped over the same time period from over 11.4 mt (12.6 tn) to 9.9 mt (10.9 tn), while ready mix concrete production has increased at a compound annual growth rate of approximately 4% per year over the same time period (NRMCA 2024b). The use of coal fly ash in blended cement and clinker production has remained relatively constant at approximately 3.0 mt (3.3 million tn) (ACAA 2009, ACAA 2023).

Although the supply of freshly produced coal fly ash is shrinking, there are massive reserves of coal ash in landfills and impoundments, and ash producers are increasingly turning to these deposits to meet demand from the concrete industry. In 2022, it was reported that over 3.6 mt (4 million tn) of harvested ash was used for a wide range of purposes, including in concrete. Although harvesting ash offers the opportunity to at least maintain current coal fly ash supply, the geographic distribution of harvesting sites and the cost of transportation will continue to impact efforts to increase the use of coal fly ash in concrete, as will federal and state regulations governing the harvesting and transportation of coal ash.

Slag cement is the next most common SCM in the United States, but in terms of supporting the increased production and use of blended cement, growth in slag supply is not expected. Unlike natural materials or the special case of coal ash, there are no reserves of slag cement. Slag for use in concrete comes from the production of pig iron in blast furnaces, and blast furnaces are meeting the same fate as other energy- and carbon-intensive technologies. Steel production is trending away from blast furnaces and basic oxygen furnaces toward electric arc furnaces. According to the USGS, steel production in electric arc furnaces accounted for an estimated 71% of US steel production in 2023 (USGS 2024). The amount of granulated slag shipped in the United States in 2021, the most recent year for which data are available, was estimated to be 3.0 mt (3.3 million tn). The total amount of iron slag, including air-cooled and granulated, was 7.6 mt (8.4 million tn).

In comparison, 8.1 mt (8.9 million tn) of steel slag was shipped in 2021 (USGS 2024). These numbers include imported slag, which accounted for approximately 13% of the total. Approximately 99.8% of the granulated slag is used as a cementitious material in concrete (USGS 2024).

Although blast furnace iron production is in decline in the United States, slag will continue to be produced in other countries and imported to the United States. The supply of slag is not expected to grow in proportion to the expected growth in concrete, but slag will be an available option for the foreseeable future, albeit at approximately the same level of supply as has historically been the case. Imports will bring slag into new markets (e.g., the west coast of the United States), thereby diversifying the geographic distribution of slag cement.

Given these challenges, there is a need to find other sources of SCMs to allow for higher substitution rates in blended cements. To that end, a number of materials have been investigated. However, the sheer volume of material required to meet demand all but eliminates most options. The one exception is calcined clay. Calcined kaolinite clays have been used in concrete in the past and have demonstrated very good performance.

History of Calcined Clay in Cement

Use of calcined clay as a cementitious material can be traced back to the earliest days of modern concrete. For example, a blended portland-pozzolan cement was produced in the 1910s by the Santa Cruz Portland Cement Company using portland cement and a “calcined Monterey shale” (Meissner 1950). That cement was used by the California Division of Highways in a number of structures, including an experimental concrete highway (Meissner 1950). Following successful field and laboratory trials demonstrating resistance to alkali soils and sulfate-laden water, the same portland-pozzolan cement was used in the San Francisco anchorages of the Bay Bridge and the Golden Gate Bridge (Meissner 1950). These anchorages were recently inspected and were deemed to be in good structural condition (Riding and Zayed 2020). In the same era and into the mid-20th century, portland-pozzolan cements were used extensively by the Bureau of Reclamation for dam construction, taking advantage of the demonstrated durability as well as the reduced heat of hydration typical of these blends (Davis 1950). In the mid-20th century, given its low cost and widespread availability, coal fly ash became more commonly used as a pozzolan following the groundbreaking research of Davis et al. (Davis et al. 1937). As a result, the use of calcined clays and natural pozzolans waned (Riding and Zayed 2020).

In the 21st century, calcined clays and natural pozzolans are having a rebirth given the reduction in the supply of coal fly ash along with an increased demand for SCMs to achieve carbon-reduction goals. In particular, interest in calcined clay has grown given the abundance of useable clay on Earth. Although calcined clay has been used previously, as described, the approach of combining calcined clay and limestone to significantly reduce the clinker content of blended cement was only first reported in 2012. (Antoni et al. 2012, Sharma et al. 2021).

LC^3 Technology

Like other hydraulic blended cements, LC^3 combines portland cement with other constituents to produce a final product that performs as well as, or better than, portland cement blended with any of the blended constituents alone. For example, Type IP blended cement combines portland cement with a pozzolan, commonly coal fly ash, though other pozzolans such as calcined clay are used. Such blends can accommodate up to about a 30% pozzolan substitution for clinker; further substitution will begin to impact concrete performance relative to the use of portland cement only (Antoni et al. 2012). In some cases, the reduction in performance is not important given the performance requirements of the specific application (e.g., applications in which a reduction in strength can be accommodated). In these cases, higher substitution levels can be achieved. In other cases, the reduction in performance may be limited to a certain age, such as in blends that reduce early-age strength. Nonetheless, given that a pozzolan is less reactive than cement, there is a limit to the substitution for clinker that can be used to attain a specified performance level.

As another example, a Type IL blended cement combines portland cement with 5% to 15% limestone. In the presence of portland cement, limestone will react to form carbo-aluminate hydrates, but only about 5% of the limestone will react (Antoni et al. 2012). This reaction does contribute to the performance of the blended cement, and the remaining unreacted limestone contributes by serving as a filler to initiate the formation of hydration products (Berodier and Scrivener 2014, Lothenbach et al. 2008).

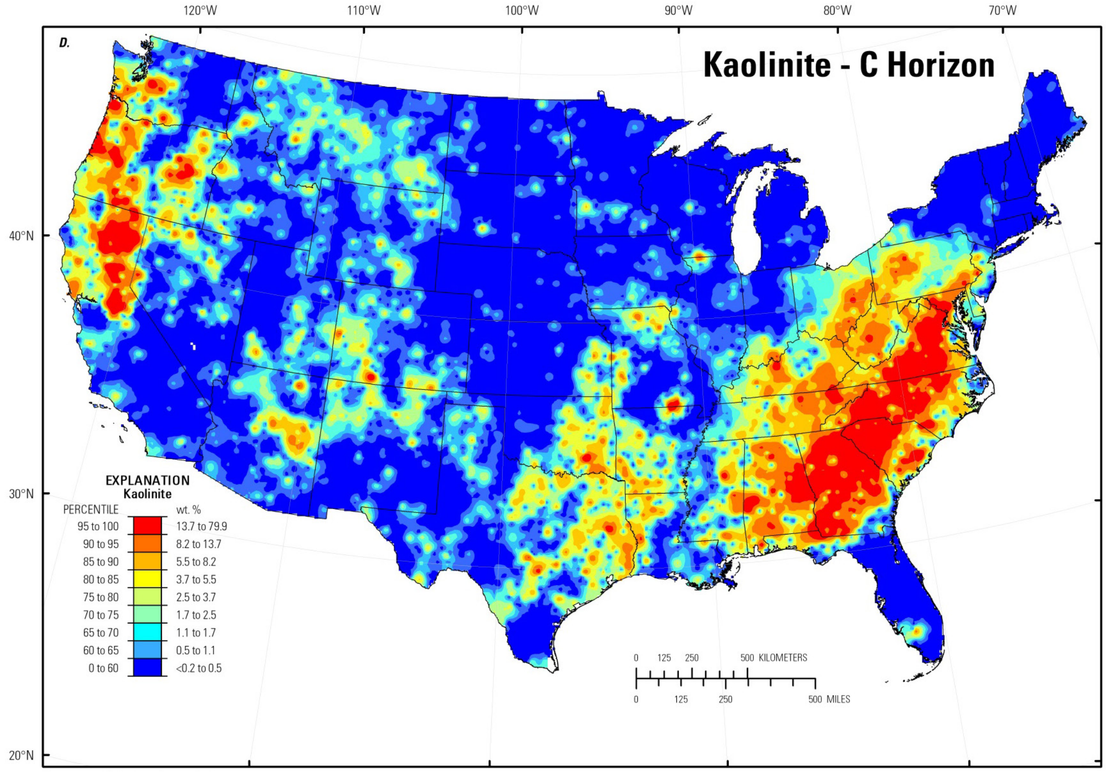
An LC^3 cement combines both a pozzolan (i.e., calcined clay, an alumino-silicate pozzolan) with limestone and portland cement clinker. The proportions of each blended constituent are similar to those used in a binary blended cement: 30% substitution of pozzolan and 15% substitution of limestone. The alumina from the calcined clay reacts with the excess carbonate from the limestone to form carbo-aluminate hydrates beyond those formed with portland cement alone.

The filler effect of the limestone and the added fine clay particles further enhances the formation of hydration products to improve strength and provide pore refinement to reduce permeability (Scrivener et al. 2018, Zunino and Scrivener 2019). The net result of using the ternary blended cement approach is the potential to reduce the nominal clinker content to 50% or less; for comparison, a Type IP(30) cement has a nominal clinker content of 65%, and a Type IL(15) cement has a nominal clinker content of 80%. Note that these proportions assume a nominal 5% calcium sulfate content.

Although a Type IL(15) cement is used as the example in the discussion above, in practice, given the tolerance of limestone content in AASHTO M 240 (ASTM C595) of ±2.5%, a blend such as a Type IL(13) cement represents a more practical limit. The actual proportions of an LC^3 mixture will vary depending upon the physical and chemical characteristics of the clinker and the kaolinite content of the calcined clay (Sharma et al. 2021, Zunino et al. 2021). The clinker impacts the blend proportions because the chemical reactions of the calcined clay and the limestone will depend on the calcium hydroxide available in the cementitious system, which in turn will be determined by the alite and belite content of the clinker. For an LC^3, the nominal ratio of calcined clay to limestone is 2:1 when using a calcined clay with a kaolinite content of approximately 40% (Sharma et al 2021). If the kaolinite content increases, the ratio of calcined clay to limestone can be varied, reducing the amount of calcined clay needed and further reducing the overall carbon footprint of the blend. Likewise, the sulfate content must be adjusted beyond that needed to balance the C_3A in the clinker given the additional alumina provided by the calcined clay (Sharma et al 2021).

Sources and Production of Calcined Clay

Kaolinite clay is found in various locations around the United States. It forms from the weathering of feldspar minerals, followed by the leaching of calcium, sodium, and potassium, which leaves the alumina and silica-rich remainder (Smith et al. 2019). Figure 5 shows a heat map of the known kaolinite deposits in the continental United States. The data used to construct the map in Figure 5 were obtained from a low-density sampling process of materials occurring approximately 1 m in depth below the surface (Smith et al. 2014). In Figure 5, a change from blue to red indicates an increase in kaolinite in the sampled material. The map illustrates the geographic distribution of kaolinite, with the southeastern states being most prominent, particularly a band that runs from Virginia to Alabama. There are also significant deposits in California and the Pacific Northwest, as well as in the central United States. LC^3 production has the most immediate potential in these areas, but shipping to most major markets is feasible.



Smith et al. 2014

Figure 5. Map showing the relative abundance of kaolinite clay in the continental United States

Metakaolin is a form of calcined clay currently used in limited concrete applications that is produced using high-purity kaolinite clay (i.e., clay with a kaolinite content of over 70%). In contrast, clays containing 40% to 60% kaolinite can be used to produce an LC^3 cement that has been shown to have similar performance to portland cement (Scrivener et al. 2019, Zunino et al. 2021). The same research showed that using clay with more than 50% to 60% kaolinite provided insignificant improvement with respect to compressive strength. Sources of suitable clay include waste from other mining operations, further expanding available sources (Riding and Zayed 2020). The kaolinite content is one of the key factors in selecting a clay to process. Low-grade clays (i.e., clays with a kaolinite content of less than 40%) may be beneficiated to increase the kaolinite content of the feed to a calcining process (Zunino et al. 2021).

An LC^3 cement is produced by either intergrinding calcined clay with clinker, limestone, and calcium sulfate or by blending portland cement with ground limestone and calcined clay. Due to the grinding and storage limitations of cement producers, blending a Type IL cement with calcined clay is more common in the United States than in other countries. Research has shown that separately grinding the constituents and then blending yields the best performance (Scrivener et al. 2018). This is due to the difference in hardness between clinker and both calcined clay and limestone. Because of this difference, intergrinding leads to a bimodal particle size distribution, where clinker particles are coarser, reducing their reactivity and therefore reducing early strength, and clay particles are finer, enhancing their reactivity, which could lead to issues of workability. Blending allows for an engineered particle size distribution that optimizes the overall reactivity of the blended cement. However, interground LC^3 blends have been produced that do perform well (Scrivener et al. 2018).

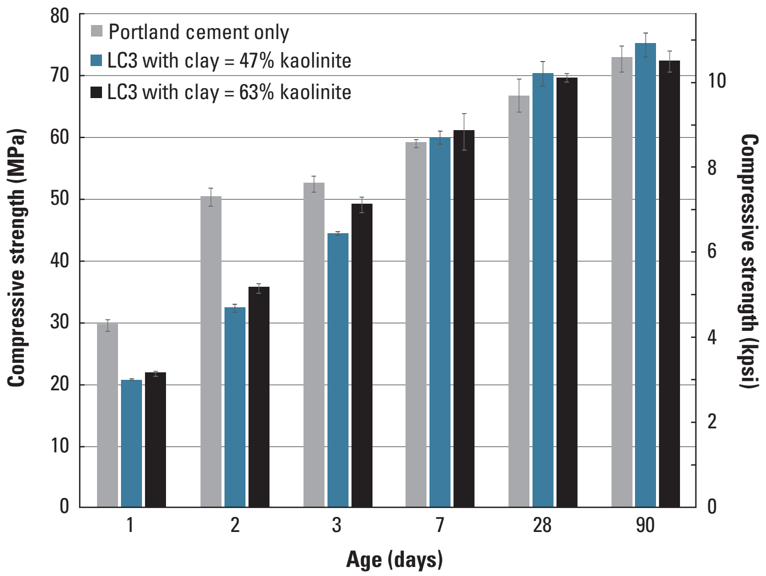
The unit operation of calcining involves heating a solid to remove a volatile component at temperatures below the melting point. Although the basic calcination operation is the same for both clay and limestone, there are significant differences. First, clay is calcined at temperatures much lower than those used in clinker production to calcine limestone. The optimal temperature range for calcining clay is 700°C to 850°C (1,300°F to 1,550°F), depending on the clay type (Scrivener et al. 2018). In comparison, temperatures for clinker production can be as high as 1,450°C (2,600°F). Second, the process of calcining clay only emits water, not CO_2, while calcining limestone yields approximately 440 kg CO_2 per mt (880 lb CO_2 per tn) limestone calcined, just from the chemical conversion of calcium carbonate to calcium oxide. This does not include the CO_2 associated with the fuel combusted to achieve the higher clinkering temperatures needed for portland cement. The GWP reduction associated with LC^3 is accomplished by substituting less impactful calcined clay and limestone for the higher-GWP clinker. The process of calcining clay can be accomplished in a variety of unit operations, including a rotary kiln, flash calciner, or a fluidized bed (Scrivener et al. 2018). Research has not shown significant performance dependence on the method used. The primary consideration is the cost and the available fuels (Scrivener et al. 2019).

Another important consideration for LC^3 production is achieving sulfate balance in the final blended cement. Sulfate in the form of gypsum, anhydrite, or hemihydrate is combined with clinker to produce portland cement. The sulfate is used to control the reaction of the C_3A phase in the cement, which reacts early and quickly. Calcined clay adds additional alumina to the mixture that will consume the sulfate, leaving the cement under-sulfated. It is therefore necessary to optimize the sulfate balance of the LC^3 blend (Antoni et al. 2012, Scrivener et al. 2018, Scrivener et al. 2019).

Performance of LC^3

Compressive Strength

As stated previously, properly formulated LC^3 blended cements can provide performance that equals or exceeds that of a portland cement. Figure 6 provides mortar test data illustrating this point. The grey bars are compressive strength data from mortars prepared using portland cement only. The green bars are compressive strength data from mortars prepared using an LC^3 blended cement that uses 50% clinker, 30% calcined clay, and 15% limestone. The calcined clay is nominally 47% kaolinite clay. The black bars are compressive strength data from mortars prepared using an LC^3 blended cement that uses the same 2:1 ratio of calcined clay and limestone, but the calcined clay is nominally 63% kaolinite clay (Zunino et al. 2021). At early ages, the portland cement samples have a higher compressive strength relative to the LC^3 samples, but at 7 days and beyond, the compressive strengths of the LC^3 samples are comparable to or above those of the portland cement samples. Also note, the mortars with a higher kaolinite content did not outperform the mortars with a lower kaolinite content at later ages, providing evidence that high-purity clays are not required to achieve performance comparable to that of portland cement.



Data courtesy of Zunino et al. 2021

Figure 6. Compressive strength of mortar cube specimens prepared using portland cement only, LC³ using a clay with 47% kaolinite, and LC³ using a clay with 63% kaolinite

Water Demand and Set Time

Depending upon how the LC³ is produced, the resulting blend could have a high fineness, particularly when the clay is interground with the clinker. In those instances, a higher water demand may occur (Scrivener et al. 2019). This is a property that needs to be controlled by the producer to minimize the impact on concrete mixtures. Likewise, due to the high fineness and increased alumina content, LC³ blended cements may have a shorter set time than portland cements (Sharma et al. 2021). As seen in Figure 6, the LC³ blends do lag in terms of early strength in spite of their faster set time. There is some data on the performance of LC³ blends with available admixtures, and, in general, the difference in particle morphology seen in calcined clay may have an impact on admixture performance (Sharma et al. 2021). Required dosages may vary from what is required for portland cement. In terms of water reducers, available research shows that LC³ blends tend to respond better to polycarboxalates than to sulphonated naphthalene formaldehyde-based water reducers (Sharma et al. 2021). Slump retention has been shown to improve with use of a retarder (Sharma et al. 2021).

Durability

An important characteristic of a hydrated LC³ blended cement is the refined pore structure that results. Although the total porosity in the microstructure of an LC³ blend tends to be higher than that found in hydrated portland cement, the pore size distribution is finer and more tortuous, resulting in reduced permeability (Antoni et al. 2012, Sharma et al. 2021). In turn, this reduced permeability reduces chloride ingress and increases resistivity (Sharma et al. 2021). Chloride penetration is reduced by the finer pore structure, and there is some evidence that chloride binding is increased due to the higher alumina content (Sharma et al. 2021). Current research on the impact of carbonation is not conclusive. On the one hand, in the microstructure of a hydrated LC³ blend there are fewer phases that may carbonate, so carbon dioxide may penetrate to a greater depth faster. On the other hand, the refined porosity limits water ingress and negatively impacts the corrosion current. Additional studies are necessary to fully understand the impact of carbonation (Sharma et al. 2021).

Regarding ASR, research has shown that LC³ mortars are not susceptible to ASR when tested with known reactive aggregates. This is a consequence of the reduced alkalinity associated with the clinker reduction coupled with the impacts of the calcined clay, which is an effective pozzolan. This is a major benefit of using LC³ cements in the United States, where ASR is a significant problem for pavement construction. Likewise, LC³ blends have been shown to improve sulfate resistance, and that effect increases with increasing clinker replacement (Sharma et al. 2021).

One area where data are lacking is on the impact of LC³ blends on cyclic freezing and thawing durability. As these cements are introduced in North America, where freezing and thawing tends to be more severe than in other locations, research will be required to assess performance.

It is expected, however, that resistance of LC³ blends to cyclic freezing and thawing will be comparable to or better than that of portland cement, given the lower permeability characteristics of hydrated LC³ blended cements.

Environmental Impact

It is not possible to develop a single comparison between LC³ blended cements and any other cement type given the number of factors that must be considered. For any cement, the fuel and electrical energy sources required for production vary, and transportation costs for raw materials or for getting a product to market vary geographically. In the case of LC³ specifically, there are multiple approaches to production that may include different types of calciners, choices between intergrinding and blending, and considerations regarding the transportation of intermediate products (e.g., moving calcined clay from a calciner to a blending facility). Likewise, the production of portland cement or other blended cements has a similar array of variables.

In the end, a life-cycle assessment (LCA) needs to be performed for the given situation to accurately establish the GWP of a given cement product. That said, some general observations can be made. First, unlike industrial wastes such as coal fly ash, which have very little embodied carbon allocated to the product, calcined clay does have an energy and CO_2 footprint. Therefore, pozzolan- or slag-blended cements will often have a lower GWP. Where slag and coal ash are available, they may be better alternatives to achieve carbon reduction goals. However, coal ash and slag are not universally available and are currently in short supply in some markets. Compared to clinker, the calcination of clay requires about 60% of the energy and produces approximately 30% of the CO_2 emissions (Sharma et al. 2021). When the totality of the LC³ process is considered, in general, the energy requirements are about 15% lower and the CO_2 emissions are 30% to 40% of those associated with portland cement production (Sharma et al. 2021). Therefore, LC³ provides a significant reduction in the GWP of concrete overall and will increasingly be an alternative for concrete producers.

Specifications

Currently, an LC³ blended cement can be specified under AASHTO M 240 (ASTM C595). However, these specifications limit the limestone content to 15%, and when tolerances are considered, the practical limit is closer to 13% limestone. Therefore, if the 2:1 ratio for calcined clay to limestone is maintained, assuming a calcium sulfate content of 5%, the resulting blend would be approximately 56% clinker. This represents a significant improvement over portland cement alone but does fall short of what is possible. As stated previously, the 2:1 ratio may vary depending on the reactivity of the clay (Sharma et al. 2021), meaning that some LC³ blended cements can be produced under AASHTO M 240 (ASTM C595). However, the opposite may also be true, and future clinker reductions beyond 50% will likely require limestone contents greater than 15%. A higher limestone content can be used if the LC³ blend is specified under ASTM C1157 or if a local specifier agrees to the higher limestone content. This is an option in a limited number of states given that most SHAs have not approved ASTM C1157 cements for use.

Currently, ASTM International is discussing a proposal for a new blend type to be included in ASTM C595, and the same type has been proposed for addition into AASHTO M 240. This would be called Type IC hydraulic composite cement. The exact details are still under discussion, but the general approach would be to establish a maximum of 70% for any combination of limestone, pozzolan, and slag, without restriction on the number or quantity of each blending constituent. If slag is used in the amount of 70% or greater, a maximum of 95% will apply for any combination of limestone, pozzolan, and slag. Under this new blend type, a 50% portland cement LC³ blend could be more readily produced, and there would be the future possibility of reducing the clinker content below 50% while maintaining necessary performance characteristics. This latter step will become important when further carbon reductions are being pursued.

Emerging Technologies: Low-Clinker Blends

To achieve industry carbon reduction goals, the primary approach will be the reduction of clinker content, which necessarily requires the use of a blended cement because something needs to replace the clinker fraction. Technologies such as LC³ are currently used internationally and are pushing the clinker content of cement toward 50%. As the industry continues toward net-zero-carbon concrete, the clinker factor will necessarily need to be reduced further. However, not all applications can move to 50% clinker or less, depending on the specific cement and application. A lower clinker content, in many cases, may lead to reduced ultimate strength or longer strength development times, making these cements unusable in some applications.

To achieve further clinker reduction in blended cements, new technologies are emerging. One example is high-filler, low-water (HFLW) cement blends. This type of blended cement centers around optimizing particle packing by selecting combinations of materials with specific size distributions (UN Environment Programme et al. 2018, Vanderley et al. 2018, Cruickshank et al. 2023). The production of this type of material requires the cement constituents to be ground, sized, and blended separately.

These blends make use of very high filler contents, which leads to practical challenges. A key issue with fillers in general is increased water demand. This problem can be partially addressed by optimizing particle packing (i.e., engineered particle size distribution), which minimizes the space to be filled with water between the particles (UN Environment Programme et al. 2018, Vanderley et al. 2018), and by using superplasticizers to further improve workability (Proske et al. 2017). The basic principles of cement hydration suggest that a close-packed particle structure with minimal water-filled space, once hydrated, will also be a low-permeability structure and can result in improved durability (Bertin et al. 2023). The clinker contents in these types of blends are typically 30% or less, and fillers such as ground limestone can constitute 50% of the blend or more, the balance being a high-performance SCM such as slag, fly ash, or calcined clay.

Commercially available products of this type are being produced and marketed in Europe, and these products are moving to the US market. Compared to portland cement, some of these high-filler blended materials claim to reduce carbon by as much as 70% (Ecocem 2024) with performance that equals or exceeds that of ordinary portland cement (UN Environment Programme et al. 2018, Proske et al. 2017, Ecocem 2024). Currently, these types of blends can be specified under ASTM C1157, but as AASHTO M 240 (ASTM C595) continues to evolve, these types of materials will eventually be included.

Closing

The concrete construction industry is faced with a monumental challenge: to be carbon neutral by 2050 or sooner. The transportation sector of the industry is not immune to this challenge, and in fact the transportation sector is looked to for leadership in the adoption of new materials. SHA specifications are the default specifications for the concrete industry, and as the SHAs go, so goes the rest of the industry. Blended cements have been part of the construction industry for over 100 years but have not been widely used until recently. Without question, however, the use of blended cements will only increase in the immediate future. While the performance of blended cements has been established, they still need to be implemented, which will require cooperation between all stakeholders. The production and use of blended cements will be an important component of achieving the concrete construction industry's sustainability goals but also offer exciting opportunities to improve the durability of concrete and the resilience of transportation infrastructure.

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About the National Concrete Pavement Technology Center

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