TECHNOTE

Portland Limestone Cement

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INTRODUCTION

Portland limestone cement (PLC) is a binary blended cement manufactured according to ASTM International (ASTM) C595[1] or American Association of State Highway and Transportation Officials (AASHTO) M 240.[2] PLC contains 5- to 15-percent blended or interground limestone and is alternatively identified with the term "IL," which indicates portland cement-limestone blended cement in ASTM C595 and AASHTO M 240.[1,2] PLC is engineered to provide 28-d performance equivalent to that of ordinary portland cement (OPC) (ASTM C150[3] or AASHTO M 85[4]) for 1:1 replacement while reducing global-warming potential (GWP) 8.3 percent on average, thanks to its lower clinker content.[5] Cement suppliers are typically producing PLC with 10- to 12-percent limestone powder because such a blend results in a more optimal, 1:1 performance.

Though PLC has now become widely available throughout the United States, several agencies and contractors have reported challenges with its implementation due to limited field experience using the material in the United States.[6] This TechNote is designed to help State highway agencies (SHAs) and contractors become more acquainted with technical and background information regarding PLC and to promote its successful application nationwide. The document provides information regarding the history, specifications, sustainability, manufacture, engineering principles, and performance of PLC. In addition, the document presents successful case studies and best practices for implementing PLC.

History of PLC in the United States

ASTM C150 began allowing the use of up to 5-percent interground limestone in OPC types I–V in 2004.[3] Before then, in North American specifications, limestone had not been permitted as an addition to cement. AASHTO M 85 was harmonized with ASTM C150 in 2007, when the 5 percent allowable limestone content for OPC was balloted and accepted.[4] PLC was introduced in the United States in 2005 through ASTM C1157 as a performance cement.[7] While cements with high ground limestone contents have been successfully used in Europe for 15–20 yr, North American PLC differs in that it was designed to have mechanical properties similar to those of OPC at 28 d, and the concrete producers often add supplementary cementitious materials (SCMs) to PLC.[8] Beginning in 2012, ASTM C595 and AASHTO M 240 standard specifications for blended hydraulic cements started allowing up to 15-percent blended or interground limestone to be used in binary blended cements, and the specifications defined the product as IL or PLC.[1,2] While PLC has been allowed in many States since 2012,

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only producers in Utah and Colorado were using PLC in significant quantities.

Thanks to continuous research and education initiatives such as the Transportation Research Board (TRB) workshop in 2012, successful implementation cases, and increasing concerns regarding the sustainability of the cement and concrete industries, the use of PLC has been steadily increasing in the United States since its introduction.[9] A survey sponsored by the Portland Cement Association reported that around 890,000 metric tons of PLC were produced in the United States in 2016.[10] A U.S. Geological Survey mineral industry survey reported that 24 million metric tons of blended cements were imported into or manufactured in the United States from January to November 2022, the vast majority of which was expected to be PLC.[11] PLCs are progressively replacing Type I and Type I/II cements in most plants, making OPC Types I and I/II more difficult to find in some regions.

REVIEW OF ASTM C595 AND AASHTO M 240 HIGHLIGHTS

ASTM C595 and AASHTO M 240 specifications prescribe a list of performance and constituent requirements for blended hydraulic cements that use slag, pozzolan, limestone, or some combination of them.[1,2] The two standards use a naming convention in which "PLC" is designated as "Type IL(xx)," where "xx" designates the percentage of limestone in the blend. For example, Type IL(10) designates a binary blended cement with 10-percent limestone. Additional suffixes can be added ahead of the cement name based on special properties, such as "(MH)" for "moderate heat of hydration" or "(HS)" for "high sulfate resistance." The next sections describe the chemical and physical requirements for PLC that ASTM C595 and AASHTO M 240 specify.[1,2] Table 1 provides a summary of these requirements.

Table 1. Chemical and physical requirements for PLC from ASTM C595 and AASHTO M 240.[1,2]

<table>
<tr><th>REQUIREMENTS</th><th>ASTM STANDARD</th><th>AASHTO STANDARD</th><th colspan="2">PROPERTY</th><th>SPECIFIED LIMIT FOR PLC</th></tr>
<tr><td rowspan="2">Chemical</td><td rowspan="2">C114[15]</td><td rowspan="2">T 105[16]</td><td colspan="2">Sulfur reported as sulfate (SO_3), maximum, percent</td><td>3</td></tr>
<tr><td colspan="2">LOI, maximum, percent</td><td>10</td></tr>
<tr><td rowspan="6">Physical</td><td rowspan="2">C191[17]</td><td rowspan="2">T 131[18]</td><td rowspan="2">Time of initial set, Vicat test</td><td>Set minutes, not less than</td><td>45</td></tr>
<tr><td>Set hours, not more than</td><td>7</td></tr>
<tr><td>C185[19]</td><td>T 137[20]</td><td colspan="2">Air content of mortar, volume percent, max</td><td>12</td></tr>
<tr><td rowspan="3">C109/
C109M[21]</td><td rowspan="3">T 106 M/
T 106[22]</td><td rowspan="3">Compressive strength, minimum, megapascals (psi)</td><td>3 d</td><td>13.0 (1,890)</td></tr>
<tr><td>7 d</td><td>20.0 (2,900)</td></tr>
<tr><td>28 d</td><td>25.0 (3,620)</td></tr>
</table>

Chemical Requirements

Limestone used in the manufacture of PLC or a ternary blended cement is required to have a calcium carbonate content of at least 70 percent by mass, which is determined by multiplying the calcium oxide content of the limestone by a factor of 1.785,[1] which is the ratio between the calcium carbonate and calcium oxide molar mass. A 3-percent maximum sulfate (SO_3 when expressed as sulfur trioxide) content is specified for PLCs and for ternary blends in which the limestone content is larger than or equal to slag or pozzolan.[1] For these cements, no maximum chemical limit is imposed on magnesium oxide, sulfide (S_2-), or insoluble residue content. The sulfate limit was set mainly to maximize the potential reactivity of the calcite in the system.[12] However, when pozzolans with high alumina content (e.g., slag, metakaolin, or high alumina fly ash) are included in the blended cement, the performance may be improved by having SO_3 concentrations higher than 3 percent.[13] Because of that potential improvement, ASTM C595[1] and AASHTO M 240[2] allow for SO_3 contents higher than 3 percent, provided ASTM C1038/C1038M is used to demonstrate that the cement with the increased SO_3 content will not develop expansion exceeding 0.020 percent at 14 d.[14] This sulfate optimization may assist with optimizing strength or setting time. For PLC and ternary cements, the maximum loss on ignition (LOI) is specified as 10 percent to control the cement limestone content and potential moisture contaminations.[15,16]

While not specifically mentioned in ASTM C595, due to the wide range of limestone contents allowed in PLC, Bogue equations cannot be applied to calculate the main cement phases (i.e., alite, belite, tricalcium aluminate, and ferrite).[1] The cement phases of PLC can be quantified reliably only by means of x-ray diffraction analysis.

Physical Requirements

ASTM C595[1] and AASHTO M 240[2] define physical limits for PLCs with respect to minimum and maximum time of initial setting by Vicat test (ASTM C191[17] and AASHTO T 131[18]), maximum air content (ASTM C185[19] and AASHTO T 137[20]), and minimum compressive strength at 3, 7, and 28 d (ASTM C109/C109M[21] and AASHTO T 106M/T 106[22]). Blended cements that incorporate accelerating or retarding elements such as admixtures are not required to meet the time of setting requirements listed in table 1. Blended cements with special properties (e.g., MH or HS) have separate physical requirements. Testing time, sampling methods, and specimen-handling requirements are all described within ASTM C595 and AASHTO M 240.[1,2]

WHY SWITCH FROM OPC TO PLC?

Cement production was responsible for 0.86 percent of U.S. carbon dioxide (CO_2) emissions in 2020.[23] Those emissions originate mainly from three major processes:

- The use of fuels to raise the cement kiln temperature to around 1,500 °C.
- The decomposition of calcium carbonate (calcination) in the cement kiln during the transformation of raw materials to clinker.
- The transportation of materials (raw materials to the cement kiln and the finished product to the users).

With the overarching goal of becoming carbon neutral industries by 2050, the cement and concrete industries have been exploring different strategies to progressively reduce their carbon emissions.[24] For example, almost all cement plants now implement a dry-kiln process instead of using the previous, wet-kiln process.[25] This change in the manufacturing process reduces the amount of fuel needed to heat and dry the raw materials during the clinkering process by predrying them using waste heat from the cement kiln.[26] Another strategy that has become more widely adopted involves the use of alternative, low-emission fuels (such as natural gas) or waste fuels instead of the more traditional, coal-based fuels.[27] By implementing these and other more energy-efficient strategies, cement producers have progressively reduced the carbon footprint related to cement production.[28,29]

In parallel to the cement industry, the concrete industry has been investigating options to further reduce its carbon emissions. Two of the most promising implementation-ready strategies being explored are the production of durable concrete with reduced cement content and reduced clinker content.[30] Reducing the cement content can be achieved by, for example, minimizing the paste content in concrete by optimizing aggregate gradations or increasing the use of SCMs. Cement can also be manufactured with a lower quantity of clinker.[30] PLC is an example of a lower clinker cement and constitutes an additional tool to further reduce the carbon emissions of concrete while still ensuring adequate performance.[31]

IMPACT ON EMISSIONS

The main motivator for switching from OPC to PLC is to reduce CO_2 emissions from the cement and concrete industries. Environmental product declarations (EPDs) are the most commonly used tools for quantifying the sustainability of cement and concrete. Based on the industry-average EPDs for OPC and PLC, PLCs reduce GWP by 8.3 percent on average.[29,32] Using field and laboratory concrete paving mixture designs to develop GWP values for the A1 to A3 lifecycle stages of the concretes, PLCs tend to result in GWP reductions of up to 10 percent, as shown in figure 1.[5] The amounts of limestone powder and cement significantly influence the impact of PLC on concrete's embodied emissions.

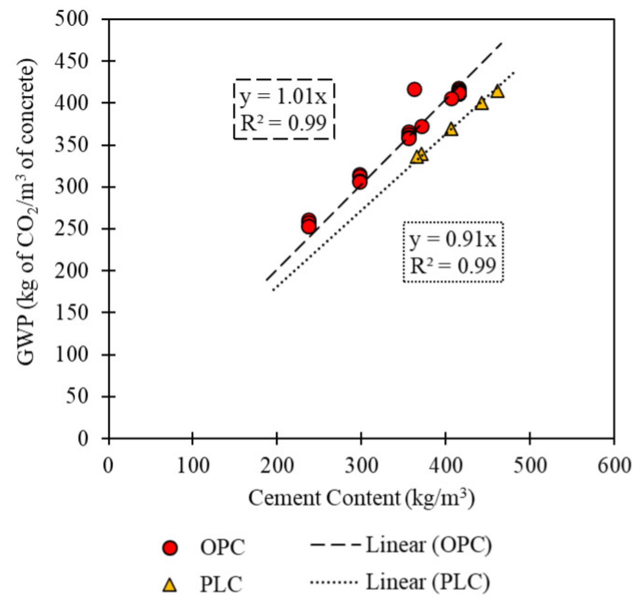
HOW IS PLC MANUFACTURED?

The PLC and OPC manufacturing processes are similar, with the primary exception being that a greater portion of the clinker is replaced with limestone powder in PLC. Typical limestone contents in PLC range from 10 to 15 percent instead of the typical 2 to 4 percent found in OPC. The added limestone is first heated to remove inherent water and is later blended or interground with the clinker and gypsum. Because the limestone has a lower hardness than the clinker, it is typically ground to a finer particle size (figure 2).

Concrete mixtures produced with the resulting PLC have been shown in several studies to perform similarly to comparable mixtures produced with OPC alone. (See references 8, 9, 31, and 34.) To ensure similar performance by PLC and to offset dilution of the clinker content, PLC is typically ground to a higher fineness than regular OPC. The increased fineness of PLC is reflected in a higher Blaine fineness (generally 10–30 percent higher for PLC than for OPC) or in a finer particle size distribution, which is influenced partially by the greater quantity of smaller limestone particles.[33]

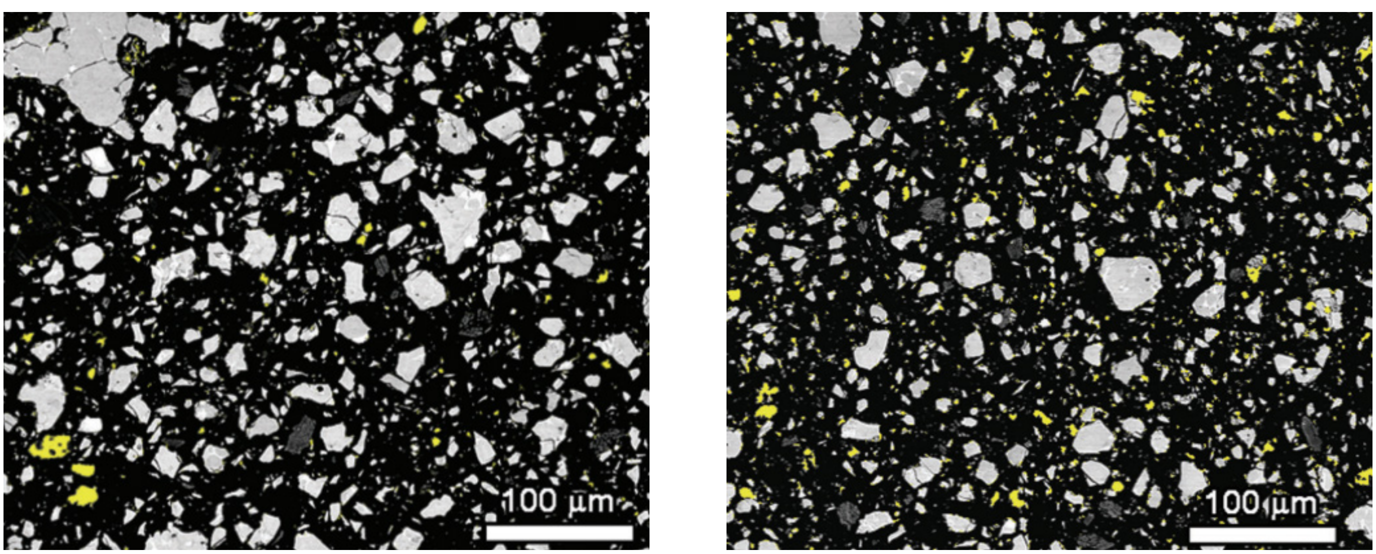
One important consequence of the increased limestone content in PLC is the decrease in the total energy consumption and CO_2 released during its production when compared with OPC.[8] Because limestone avoids the calcination process and is not heated to the 1,500–2,000 °C that the clinker requires, less fuel is used and less CO_2 from limestone decomposition is released into the atmosphere. Moreover, no additional transportation-related costs and CO_2 emissions are typically experienced, since the same limestone source used in the clinker production can be used as partial clinker replacement.

Figure 1. Graph. OPC-concrete and PLC-concrete GWPs from the A1–A3 lifecycle stages compared with cement content.



Source: FHWA.

Figure 2. Photo. Scanning electron microscopy images of OPC and PLC illustrating ground clinker (gray) and ground limestone (yellow).[34]



A. OPC.

B. PLC.

In addition to reduction in the CO_2 produced, less limestone is used in the manufacture of the same quantities of PLC than OPC, thereby extending the life of the quarry. This concept may seem counterintuitive because PLC has an increased limestone content. However, because part of the limestone is lost during the calcination process—in the form of CO_2—the total quantity of limestone used in the production of PLC is reduced, since less clinker is required. That reduced quantity is an additional and often forgotten sustainability benefit of PLC.

Due to increased limestone content in the cement, some adjustments to the gypsum content may be required to ensure the PLC's proper performance. In particular, Campiteli and Florindo report a change in optimum sulfate content as a function of the limestone content and the cement fineness.[35] A change in the sulfate content of PLC may affect the way the cement interacts with other SCMs.

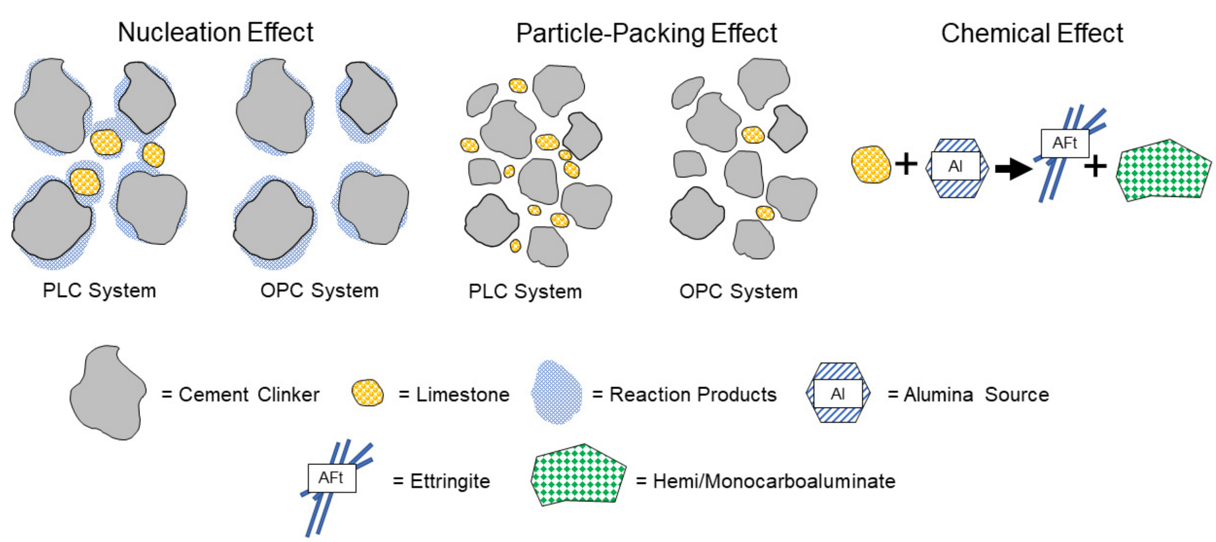
ENGINEERING PRINCIPLES BEHIND PLC AND PLC CONCRETE

Because of PLC's reduced clinker content, the total number of hydraulic reactive phases of the cement is expected to be diluted when compared with OPC. The reduction in reactive phases can potentially delay the setting time and the rate of strength development. To offset the dilution of reactive phases, PLC and PLC concrete can be engineered differently from traditional OPC and OPC concrete.[8] One example of engineering strategies, already mentioned in the manufacturing section, requires PLC to be ground finer than OPC (figure 2). The increase in fineness enhances the rate at which the cement particles can react and hydrate when in contact with water.[36]

Moreover, the additional limestone in the PLC can interact with the clinker to further enhance the performance of the system and offset any clinker dilution effect. Figure 3 provides a visual representation of the different mechanisms that enable PLC to offset loss in performance from the dilution of clinker.[8] First, the increased fineness of the limestone particle size in PLC provides additional nucleation sites (figure 3) where the products of the clinker hydration reactions can precipitate, or seed. As such, the increase in nucleation sites can accelerate cement hydration and partially compensate for the reduced clinker content at early ages.[37,38] Second, by enhancing particle packing through the filler effect (figure 3), the space between single particles is reduced and the system microstructure densified.[34] Third, a portion of the limestone can chemically react with alumina-rich phases in the system (figure 3) to form carboaluminate and ettringite phases, which can further contribute to the microstructural development of the concrete by filling the pore space.[39–41]

Although limestone is often considered an inert material or a filler, limestone can affect the reaction products of OPC and PLC systems. For example, limestone can participate in chemical reactions with alumina-rich phases in the cement and SCMs by forming carboaluminates, which can reduce setting time, decrease porosity, and increase compressive strength.[42] Because the reactivity of the limestone in PLC is tied to the presence of reactive alumina phases, it is more significant when alumina-rich SCMs such as metakaolin, slag cement, calcined clay, or natural pozzolan are used. Moreover, systems with PLCs and SCMs have also been shown to promote the occurrence of pozzolanic reactions when compared

Figure 3. Illustration. The nucleation, particle-packing, and chemical effects.



Source: FHWA.

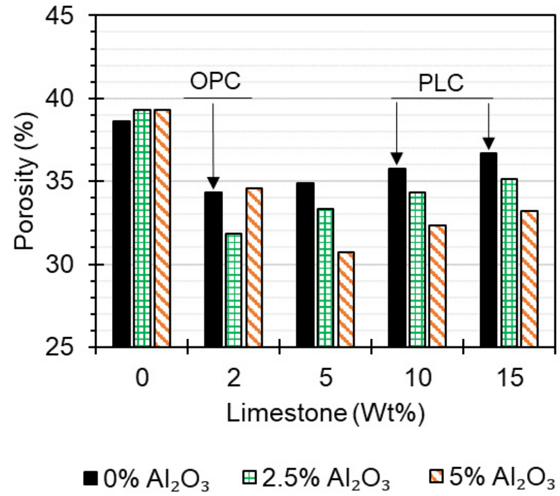
with traditional, OPC-SCM systems.[31] This increase in pozzolanic reactions can potentially contribute to reductions in pore connectivity and thus result in improved concrete transport properties (e.g., rapid chloride permeability test (RCPT) or resistivity) of concrete.[31]

To showcase the beneficial interaction between limestone and alumina-rich SCMs, figure 4 shows the synergistic effect of limestone and reactive alumina (Al_2O_3) on the porosity of pastes produced with increasing limestone replacement levels.[31] For the purposes of this study, amorphous alumina was used as a surrogate for alumina-rich SCMs. All systems in figure 4 had the same water-to-cementitious materials ratio (w/cm), and the porosity was derived from thermodynamic simulations.[31]

Figure 4 demonstrates that if no alumina is present, an increase in limestone from 0 to 2 percent (2–3 percent is a typical limestone content for ASTM C150 OPC) causes a decrease in porosity from 38 to 34 percent. At higher limestone concentrations (>2 percent), the porosity increases due to dilution of the reactive phases in the clinker. When reactive alumina is added to the system, it can react with limestone to form carboaluminate phases. These reactions can contribute significantly to reduction of the system porosity, so that a PLC system with 15-percent limestone and 5-percent reactive alumina (contributed to the system by an SCM) has lower porosity than an OPC system (2- to 3-percent limestone) with no alumina.

Figure 4 shows that for systems containing reactive alumina in the form of SCMs, PLC concretes can be engineered so that their strengths match or even surpass those of comparable OPC concretes. Moreover, optimizing the alumina content may make it possible to obtain adequate performance with limestone contents higher than 15 percent.[31]

Figure 4. Graph. Thermodynamically simulated porosity of PLC+Al_2O_3 systems, showing the synergy between limestone and alumina. (Adapted from Bharadwaj et al. 2021.[31])



Source: FHWA.

PERFORMANCE OF PLC CONCRETE

This section discusses the effect of the replacement of OPC with PLC on key concrete performance characteristics, including fresh, mechanical, volume stability, and durability properties.

Fresh Properties (Workability, Bleeding, and Setting Time)

The literature indicates conflicting results regarding the effect of limestone inclusion on the workability of cementitious materials.[33] In general, particle size distribution and particle packing are key properties of PLC that affect the fresh properties of concrete.[33] Due to its higher fineness, the limestone is expected to decrease the void space between particles by increasing the cement particle-packing density, potentially decreasing the water demand.[33] However, increased cement surface area may have an opposite effect on the water demand due to adsorption of a larger quantity of water on the surface of the finer particles. In-field adjustments for bleeding may be necessary because finer cements bleed less than coarser cements, resulting in PLC concretes that generally bleed less than comparable OPC concretes.[43] The reduction in bleeding is associated with the increased surface area of the PLC due to finer grinding, which increases the water adsorbed on the cement particles' surfaces.[33]

PLC setting time is thought to be controlled mostly by the change in cement fineness and the limestone replacement level. The literature shows different results, ranging from no influence to significant decrease in setting time.[33] A series of studies conducted on cement pastes reported a decrease in setting time of PLCs, which was somewhat proportional to the measured cement fineness.[36,44] A study by the Indiana Department of Transportation (DOT) reported that the setting time for PLC concrete mixtures was on average 10 percent shorter than the setting time of comparable OPC concrete mixtures.[34] When SCMs are combined with PLC, the reductions in the initial and final setting times may become more significant.[45,46] Differences in limestone mineralogical composition, replacement levels, and fineness might generate varied outcomes in terms of fresh properties.[34,44,47]

Mechanical Properties

When PLC is ground to the appropriate fineness, it performs comparably to OPC concrete in terms of compressive strength, flexural strength, and elastic modulus at 28 d.(34) As previously discussed, the addition of alumina-rich SCM can further promote the development of mechanical properties, potentially enabling the PLC-SCM concrete to outperform those of an equivalent OPC concrete.(40)

Volume Stability

Some SHAs have raised concerns regarding the potentially detrimental effect of the increased fineness of PLC (i.e., higher surface area) on the shrinkage and shrinkage-induced cracking of PLC concrete. The shrinkage performance of systems containing limestone is largely a function of the size of the limestone particles.(48) Coarse limestone powders demonstrated less shrinkage, while more finely ground powders demonstrated similar or slightly more shrinkage.(49) Drying shrinkage measurements have been generally found to be statistically similar in comparisons of OPC and PLC.(31,34) One exception, as identified by Bharadwaj et al., regarded the use of PLC in combination with slag, which exhibited increased total shrinkage (7- to 8-percent increase).(31) The researchers attributed the observed shrinkage increase to enhanced slag reactivity induced by the additional limestone. Barrett, Sun, and Weiss found an average increase in 28-d drying shrinkage of 5 percent when PLC concrete specimens were compared with equivalent OPC concrete.(34)

Durability

The durability indicators of PLC systems have been generally found to be similar to mixtures made with OPC.(50) Thomas et al. reported similar freeze–thaw performance, scaling, and chloride transport for PLC systems.(51) Barrett, Sun, and Weiss observed that transport properties in PLC concrete were within +/− 30 percent of comparable OPC concrete mixtures.(34) Alkali–silica reaction and sulfate testing showed that PLC concretes perform similarly to or better than OPC concretes.(8) The measured porosity, formation factor, and apparent chloride diffusion coefficient of PLC concretes were found to be comparable to those obtained for equivalent OPC concretes.(31)

CASE STUDIES

Various cement suppliers, concrete producers, and researchers have performed a multitude of case studies to investigate the performance of PLC compared with OPC. The studies incorporate plain OPCs and PLCs, as well as binary OPC and PLC concrete mixtures with the inclusion of SCMs. While this document focuses on PLC implementation in the United States, successful implementation of cements with high limestone contents has occurred worldwide. Therefore, the presented case studies discuss the use of PLC for projects in both Canada and the United States in order of the amount of valuable, new information each case study provides.

Ready-Mixed-Concrete Plant, Quebec, Canada

In 2008, a parking slab in Quebec was developed with eight different concrete materials, including plain PLC (or IL(12)) and OPC as well as binary PLC and OPC with 25-percent, 40 percent, and 50-percent SCM replacements. Performance tests included fresh air content, slump, hardened air content, air spacing factor, strength, RCPT, chloride diffusion coefficient, and scaling tests. The study found adequate mechanical and durability performance by the PLC mixtures, thereby exhibiting performance similar to that by the OPC mixtures.(8)

Cement Plant, Alberta, Canada

A cement plant in Alberta provided IL(12) cement for a project that developed pavement, retaining walls, and slipform curb.(8) The project successfully incorporated plain PLC and OPC as well as PLC and OPC with 15-percent, 25-percent, and 30-percent SCM replacements. Testing on the project included fresh air content, slump, setting time, strength, RCPT, and scaling resistance. The project observed similar performances by the PLC and OPC concretes.

Cement Plant, Nova Scotia, Canada

A concrete-paving project in Nova Scotia used blended cements that included 15-percent ground granulated blast furnace slag and two different limestone levels: 3–4 percent and 12 percent. The blended cements were then combined with fly ash at 0 percent, 15 percent, and 20 percent. After investigating the fresh, mechanical, and durability properties of the different materials, the project identified lower strength by approximately 10 percent in the PLC mixtures at later ages.(8) However, the plant attributed these lower strengths to the measured 0.02 higher w/cm ratios and 0.8-percent higher air contents of the PLC concrete compared with the OPC concrete.

40th Avenue and Havana Street, Denver, CO

A concrete-paving project in the winter of 2007 on local roads in Denver used an IL(10) with 20 percent class C fly ash.(52) The project achieved adequate compressive and flexural strength at 7 d, and the paving mixture performed similarly to comparable

OPC paving mixtures. At the time of this case study report, the pavement had sustained two winters with no visible degradation.

U.S. Highway 287, Lamar, CO

Seven miles of rural highway were paved in Lamar using an IL(10) with 20-percent class F fly ash and a total cementitious content of 540 lb of cementitious materials per cubic yard (lb/yd^3).(52) Despite being placed in hot, dry summer conditions, the concrete achieved satisfactory flexural strength performance at an age of 28 d.

I–25, Castle Rock, CO

An interstate highway section of dowel-jointed plain concrete pavement on I–25 in Castle Rock was repaved using an IL(10) with 20-percent class F fly ash, 0.42 w/cm ratio, and total cementitious content of 517 lb/yd^3.(52) Once again, the concrete obtained satisfactory flexural strength performance at 28 d.

Lost Creek Road, Morgan, UT

A rural pavement with major truck traffic in Morgan was paved using IL(10) with 20-percent class F fly ash. The concrete pavement obtained satisfactory performance with regard to compressive and flexural strength at 28 d.(53)

104th South, Salt Lake City, UT

As part of a pooled fund study with the University of Utah, a concrete pavement with IL(10) and 25-percent class F fly ash was placed in Salt Lake City. The compressive strengths at 28 d achieved satisfactory performance.(53)

Utah State Route (SR)-201, Salt Lake City, UT

The eastbound lanes of Utah SR–201 near Salt Lake City were paved with OPC, while the westbound lanes were paved with IL(10) with 25-percent class F fly ash.(9,53) The eastbound lanes achieved a higher internal pavement temperature and slightly higher strength than the westbound lanes, which Utah DOT reported as a likely result of the seasonal temperature variations between summer—when the eastbound lanes were paved—and autumn, when the westbound lanes were paved. The general contractor reported no differences in air stability or finishing quality between the OPC and PLC materials.

I–80 Reconstruction Project, Silver Creek Junction to Wanship, UT

The I–80 reconstruction project repaved 7.55 mi using OPC with 25-percent class F fly ash in the eastbound lanes and PLC with 25-percent class F fly ash in the westbound lanes.(9) The two concretes performed similarly and met all project requirements. After 10 yr in the field, both directions of transport remained in good condition.

COSTS

In general, once full market penetration is observed, PLCs are anticipated to cost similarly to OPCs.(45) Although it might seem initially that using lower cost limestone to replace clinker could result in cost savings, cement producers have highlighted a few factors that result in similar pricing between OPC and PLC. For example, the need for additional quality control operations on the material (limestone powder), the increased amounts of handling and blending that need to occur, and the increased grinding that is associated with the production of PLCs versus that of OPCs all result in similar cost evaluations between PLC and OPC.

Before reaching full market penetration, PLCs are often produced at the end or beginning of a run of OPC production at a cement plant. The increased complexity associated with producing two materials (OPCs and PLCs) and limited supply of PLC can result in initially variable costs of PLCs. For example, if PLCs and OPCs need to be produced at the same facility, PLCs require additional silo space at a concrete plant or dry storage at a bag facility. Outside of the transportation sector, however, PLCs are becoming increasingly important for their ability to help reach sustainability targets and their voluntary certification programs, which are causing PLCs to reach full market penetration scenarios. However, in markets that remain with limited PLC availability, this demand coupled with the challenges of producing both OPC and PLC may result in PLCs being considered premium materials and therefore may result in higher costs.

IMPLEMENTATION

Many concrete producers have shared that replacing OPC with PLC is accomplished without any modifications other than changing the type of cement. In general, to minimize risks and difficulties during the transition period, it may be useful to treat PLC as a cement coming from a different source and therefore implement typical control practices such as trial batching to ensure adequate performance. Some producers have noted that slight adjustments in admixture dosage or mixture proportions were needed to obtain equivalent performance.(6) These changes are consistent with what may be expected when changing cements or using a cement with a different fineness. In an effort to provide information regarding the implementation of PLCs, this section offers anecdotal observations of challenges and best practices shared by those in the industry.

Anecdotal Challenges

As more cement suppliers transition from OPC to PLC, some in the construction industry have reported PLC implementation challenges.[6] While some of the reports may be the result of increased scrutiny due to the novelty of the material, others may be consequences of slight changes in material behavior that were not accounted for ahead of construction or during trial batching. No matter the cause, this section reports anecdotal implementation challenges that those in the industry recently shared and that may be considered while obtaining experience with the use of PLC:

- Differing air contents and slump between PLC concretes and comparable OPC concretes, which may require admixture dosage adjustments before field implementation. This challenge is often experienced when changing cement fineness, aggregate particle size, or mixing action. In instances in which a decreased slump is not corrected before construction, contractors may wish to add water to increase concrete workability during field operations, which can lead to a decrease in strength and durability performance.
- Differing sulfate content requirements for PLC concretes—especially with SCMs, compared with OPC-concretes. Similarly to OPC concretes, sulfate imbalances may arise in PLC-concrete mixtures with SCMs because of differences in PLC sulfate content, which may affect setting time and strength development.
- Improper blending of limestone powder with clinker, resulting in an inhomogeneous product that can cause inconsistent performance. Materials should always be mixed and ground homogeneously to ensure appropriate performance.
- Improper intergrinding of clinker, limestone, and gypsum, which can result in an overground or underground cement that may negatively affect concrete performance.
- Decreases in early age strength or changes in strength development at low or high temperatures.
- Lower bleed rates, which may result in finishing operations occurring prematurely. This challenge is typical of concretes using finer cements. Contractors tend to use visual observations of the water on the surface of the concrete based on their experience to determine when finishing operations should begin. PLC concretes may bleed more slowly, which may result in water being trapped under the finished surface and may lead to pop-out or scaling deterioration on the concrete surface.

Best Practices

To help mitigate the previously described implementation challenges, industry members recommend possible best practices that include the following measures:

- Perform trial batches by using the same materials that will be used in the field. Performing trial batches using the same SCMs and admixtures that are planned for use in the field can improve understanding of water demands, setting time, and strength development.
- Use tools such as maturity or temperature match curing to monitor concrete strength development for projects in which strength development is critical.
- Consider the effects of temperatures on the reactivity of the material. Be prepared to use extra precaution with heating blankets or other cold-weather concreting techniques when temperatures are low. Conversely, hot weather can exacerbate reductions in workability. Adjust the mixture accordingly during trial batching and field concrete mixing to account for job site temperatures.
- Use tools such as calorimetry to investigate the early-age reaction behavior of the PLC or the PLC in combination with the anticipated admixtures and SCMs. Calorimetry can provide information on the early-age behavior of concrete, including estimations of setting time and temperature development. Use such information to adjust the concrete mixture design during qualifying operations or whenever field performance does not meet expectations.
- Use mockups or monitoring technologies to determine the optimal time between placing and finishing. Make contractors aware that the bleed rate is lower and that a visual determination of when to finish the concrete may result in adverse performance.
- Communicate early and often with cement and concrete suppliers to identify when the transition from OPC to PLC will occur and how the transition could affect projects.
- Evaluate production variation (e.g., strength or air content) prior to transitioning from OPC to PLC to provide an understanding of within-plant product variations. The use of OPC production variation data can help inform evaluation of PLC production variation.

SUMMARY

PLC provides an option to implement a proven technology for obtaining concrete with desired performance and reduced environmental impacts. PLC (ASTM C595[1]/AASHTO M 240[2]) is produced using the same clinker as that used in OPC (ASTM C150[3]/ AASHTO M 85[4]); however, PLC typically replaces 10–15 percent of the clinker with limestone instead of the typical 2- to 4-percent replacement exhibited in an OPC.[8] The reduced clinker content reduces the concrete's embodied carbon emissions. To achieve performance similar to that of OPC, PLC is ground more finely during the manufacturing process. The increased fineness helps offset the dilution of the clinker by accelerating the early-age hydration reactions and by providing additional nucleation sites for the clinker to react at. Moreover, a fraction of the limestone content in PLC is expected to react with aluminate phases, further reducing porosity. Differences in cement fineness may affect admixture demand; however, after slight adjustments to admixture dosages, PLC can be used with a seamless transition. Several studies were performed to demonstrate that in the United States. (See references 8, 9, 52, and 53.) PLC can substitute OPC with minimal changes in performance. In general, PLC has compressive strength, flexural strength, elastic modulus, shrinkage, resistance to chloride ingress, resistance to alkali–silica reaction, resistance to scaling, and resistance to sulfate attack that are similar to those of its OPC counterpart at 28-d ages. Some differences in fresh properties might result due to PLC's increased fineness. In particular, PLC concretes may experience minor losses in workability and reductions in setting times and may exhibit slower bleed rates that require more time between placement and finishing. PLC can be used with the same equipment and procedures contractors currently use. PLCs perform synergistically with SCMs; therefore, the SCMs that the industry currently uses in OPC concretes can be used for PLC concretes as well.

As the industry shifts to manufacture more ASTM C595[1] cements, PLC is becoming more available in a wider range of markets. ASTM C150[3] OPC may no longer be available in certain markets as the transition continues. Based on the volume of OPC used in the United States in 2021, the replacement of OPC with PLC has the potential to reduce CO_2 emissions by approximately 8 million tons a year, which is the equivalent of removing more than 1.7 million cars from roadways. In general, PLC can successfully replace OPC in concreting applications—with minimal changes to current practices and methods. However, this document can help ease the transition from OPC to PLC and assist in addressing challenges that may arise.

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