One of the most extraordinary things about ASTM C1157 GU performance cements is how ordinary they are. Compared to ASTM C150/AASHTO M 85 portland cements, they have similar strength gain characteristics, can be used under identical environmental conditions, are indistinguishable during mixing and placement and have similar durability characteristics.

The only major difference between the two cements is what is missing. The energy and carbon-dioxide footprint may be decreased 10% or more for ASTM C1157 GU performance cement compared with ordinary portland cement . . . and that is something extraordinary.

This is extremely important, because sustainability and sustainable design continue to grow in significance as resources grow scarce, the cost of energy increases and environmental stewardship is integrated into all elements of transportation design and construction. As a result of its relatively low cost, local availability, versatility and hallmark longevity, portland cement concrete is the most widely used building material on the planet.

This article discusses testing conducted by an independent laboratory of two ASTM C1157 GU portland-limestone cements produced by Holcim (US) Inc. in Colorado and Utah and several projects constructed using these cements to illustrate how extraordinarily ordinary these cements are.

Clinker part of clincher

So why is the manufacture of portland cement so CO₂ intensive? There are two primary sources of CO₂ inherent in the manufacturing
of portland cement. The first, which is responsible for roughly 40% of the CO₂ generated, is the burning of fossil fuels needed to acquire and process raw materials, pyroprocess the materials at high temperature to create the “clinker,” and then grinding the clinker to a powder to form cement.

The second source of CO₂, which is responsible for almost 60% of that generated, is from the predominant raw material: limestone or calcium carbonate (CaCO₃). As the limestone is heated it undergoes calcination, which releases 0.439 lb of CO₂ for every pound of limestone processed as it is transformed to CaO. On average about 0.96 tons of CO₂ is associated with the production of 1 ton of clinker in the U.S. Increasing kiln efficiency has reduced the amount of CO₂ generated in cement production over the last few decades, but even the most efficient cement kilns have a ratio of tons of CO₂ per ton of clinker in the high 0.80s to low 0.90s.

The next step in the cement process is the intergrinding of the clinker with a source of calcium sulfate (commonly gypsum) which is necessary to control the time of setting. Although some CO₂ is generated in this processing, the CO₂ per ton of cement is reduced to approximately 0.92 tons as the clinker is interground with the calcium sulfate. It is the fine grinding of clinker and calcium sulfate that creates the powder that is sold as portland cement (ASTM C150/AASHTO M 85).

The strategy of intergrinding the clinker with other inert or reactive constituents has been employed to not only reduce the carbon footprint of cement but also enhance cement performance. Some type of “grinding aids” have always been used in small quantities to assist in the grinding process. Recent modifications to ASTM C150 (and AASHTO M 85) have allowed up to 5% high-quality natural limestone to be interground with the clinker. It was commonly believed that the limestone would remain inert, but recent research suggests that most, if not all, of the limestone will chemically react in a generally positive fashion, reducing porosity and increasing strength. Unquestionably such additions have a significant environmental benefit as the replacement of clinker with limestone directly reduces the CO₂ associated with the cement.

Cements interground or blended with fly ash or natural pozzolans, slag cement and most recently a ternary combination of supplementary cementitious materials (SCMs) are available, specified under ASTM C595 (AASHTO M 240). Typical replacement rates for blended cements are 15 to 25% for those blended with pozzolans and 30 to 50% for those blended with slag cement. Ternary blends might have 15 to 30% slag and 10 to 20% pozzolan, although these can vary substantially depending on the materials. Such blended cements can reduce the tons of CO₂ per ton of cement to 0.65 to 0.80.

The recent adoption of performance-based standards (the first version of ASTM C1157 appeared in 1992) represents an important development. The cement specifications discussed thus far are largely prescriptive; that is, they are based on measured chemical and physical properties that are assumed to be related to the performance of the cement in concrete. In contrast, ASTM C1157, Performance Specification for Hydraulic Cement, simply requires that the cement meets physical performance test requirements. Under this specification, six cement types are available: GU (general use), LH (low heat of hydration), MH (moderate heat of hydration), HE (high early strength), MS (moderate sulfate-resistance) and HS (high sulfate-resistance).

For example, Types MS and HS cements use performance test ASTM C1012, Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution, to demonstrate resistance to sulfate attack. The performance classification of hydraulic cement is thus based on the concept that the material performance is of main interest, not its composition. This approach promotes innovative development of composite portland cements (portland cement intergrounded with limestone and/or blended with multiple SCMs) as well as non-portland-cement binders that have the potential to significantly lower the CO₂ associated with concrete construction.

As a relatively new specification, the acceptance of ASTM C1157 cements is currently mixed. The majority of states allow ASTM C1157 cements in their building codes, but only a limited number of state departments of transportation (DOTs) accept their use for transportation projects. The major barriers to acceptance include (1) uncertainty regarding the long-term durability of concrete made with these cements, (2) a lack of experience working with these cements and (3) there is no equivalent AASHTO specification for ASTM C1157. To address these concerns, this article discusses laboratory testing conducted on two ASTM C1157 GU portland-limestone cements produced by Holcim in Colorado and Utah and then describes the construction of several transportation structures, concrete is used for foundations, hydraulic structures, bridges, retaining walls, barriers, pavements, curb and gutter, and sidewalks. In fact, without concrete, our modern transportation system could not exist, but this versatility comes with an environmental price tag. It is estimated that worldwide, approximately 5% of the CO₂ produced by humanity (1.5 to 2% of the U.S.’s CO₂) is from the production of portland cement, which is responsible for almost 60% of that associated with the concrete typically used by transportation agencies. As a result, efforts are under way to reduce the amount of portland cement used including constructing longer-lasting structures, reducing the cement content in concrete and using cementitious materials that contain a larger volume of nonportland cement binder.

This last strategy is the one embraced by the world’s cement manufacturers and is the impetus for the development of ASTM C1157 performance cements. Although similar cements have been used for decades in Europe, the adoption in the U.S. market has been slow.
concrete pavement projects featuring the use of these cements.

**Mountain-grown results**

ASTM C1157 GU portland-limestone cements (made with 10% interground limestone) produced at two cement plants (Holcim’s Portland Plant in Colorado and the Devil’s Slide Plant in Utah) were evaluated by a third-party accredited testing agency (CTL Group, Skokie, Ill.). The ASTM C1157 GU portland-limestone cements were engineered to meet or exceed the performance of the ASTM C150 cements produced at each plant, and thus direct testing was done to compare them with their ASTM C150 counterparts.

Although the focus of this testing was on durability, fresh concrete and strength properties also were assessed. Concrete mixtures were prepared with total cementitious contents of 500 lb/cu yd and 564 lb/cu yd, with and without ASTM C618 Class F fly ash. Fresh concrete properties, including total air, slump, unit weight and bleed water, were found to be similar for all mixtures, with no discernible differences observed between mixtures made with the two cement types. Sulfate resistance of each cement blend was tested in accordance with ASTM C1012, Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution. The six-month expansion results found that all met moderate sulfate (MS) resistance requirements having expansions less than 0.10%.

Testing in accordance with ASTM C1567, Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar Bar Method), found that each cement was able to successfully mitigate ASR when used with a Class F fly ash when tested with a known reactive aggregate.

The concrete mixtures were tested for resistance to freeze-thaw damage using ASTM C666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, and resistance to deicer scaling in accordance with ASTM C672, Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals. Regardless of cement type, cement content or the replacement of cement with Class F fly ash, all mixtures showed good resistance to freeze-thaw damage and good scaling resistance.

In addition to direct durability tests, drying shrinkage was assessed using ASTM C157, Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete. No significant differences were observed between cement types for the percent drying shrinkage at 475 days. Further, chloride permeability ratings based on ASTM C1202, Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration, found little difference between concretes made with ASTM C150 and C1157 cements, although differences in ratings were observed based on cement content and whether fly ash was present, with higher cement content mixtures containing fly ash having the lowest permeability.

The results of the compressive strength testing conducted in accordance with ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, is presented in Table 1. For lower cement content mixtures, the Type GU cement always produced higher compressive strengths. With the higher cement content, the testing trend is less clear, with concrete...
made with the ASTM C1157 GU cement from the Portland Plant having slightly lower compressive strengths than concrete made with the Type I/II cement, and concrete made with ASTM C1157 GU cement from the Devil’s Slide Plant having significantly higher compressive strengths than that made with the ASTM C150 Type II/V cement from the same plant. In all cases, as would be expected, concrete made with Class F fly ash replacement had the lowest compressive strengths at the ages tested, but long-term strength would be expected to be comparable or even higher.

ASTM C1157 GU portland-limestone cements are available in Colorado by two suppliers and exclusively by Holcim in Utah. These cements are used on a regular basis in ready-mixed concrete, precast concrete products and a section of major interstate highway. The primary impetus for the use of these cements has been local and statewide efforts to address environmental concerns and lower the environmental footprint of transportation infrastructure.

Denver, for example, instituted a citywide action plan called Greenprint Denver to promote the importance of sustainable development and ecologically friendly practices throughout the community.

The 40th Avenue project, constructed in 2007, was built on the former site of Stapleton Airport, which has been redeveloped into a sustainable community. One interesting fact about this community is that all of the old airport’s concrete pavements have been recycled into 6 million tons of aggregate used in new concrete in one of the world’s largest concrete recycling projects.

In support of increasing the sustainability of the newly constructed jointed plain concrete pavement (JPCP), the 40th Avenue and Havana construction project used the Holcim Portland Plant ASTM C1157 GU portland-limestone cement with 20% Class C fly ash along with the recycled concrete aggregates. The mix was designed with 7% air and a 1.75-in. slump and placed with a slipform paver by Castle Rock Construction.

Construction took place during colder winter months, yet the mixture possessed excellent early strength gain with average compressive strength values of 1,930, 3,790, 5,220 and 6,580 psi at one, two, three and seven days, respectively. The seven-day flexural strength was 825 psi. Note these are higher strengths than specified or structurally needed, but field adjustments, later shown to be unnecessary, were made to compensate for the cold-weather placement conditions.

Quality control and field personnel did not notice any differences in batching or field placement between concrete made with ASTM C150 I/II cement used on a previously constructed section and concrete made with the ASTM C1157 GU cement. The developer, owner and contractor were all very satisfied with the performance and environmental benefits of the mixture, and the local news media reported on the environmental benefits of the “green” concrete. The project was awarded the Sustainable Pavement Award by the Colorado/Wyoming Chapter of the American Concrete Pavement Association in 2008.

The Colorado Department of Transportation (CDOT) was one of the first DOTs to allow the use of ASTM C1157 GU cement containing up to 10% interground limestone, but initially did not allow it to be blended with fly ash. This changed two years ago, and the current specification allows ASTM C1157 GU cements to be blended with fly ash added at the concrete plant, helping to meet the state’s climate action plan to lower the environmental impact of construction. Eric Prieve, CDOT concrete and physical properties engineer, summed it up: “Using ASTM C1157 cements allows Colorado to reduce greenhouse-gas emissions in the construction of concrete pavements with no compromise in quality and long-term performance.”

In their first project, CDOT used Holcim’s Portland Plant ASTM C1157 GU portland-limestone cement on a rural highway construction project on U.S. Highway 287 near Lamar, Colo. Highway 287 is part of the Ports to Plains U.S. Highway route that accommodates heavy truck traffic connecting commerce between Mexico and the U.S. Castle Rock Construction was the contractor for this $17.3 million construction project that included concrete reconstruction of 7 miles of highway and the widening of the shoulders. The project was constructed in two phases, starting in May 2008, and was completed in June 2009. The JPCP used a CDOT Class P mixture with ASTM C1157 GU cement and 20% Class F fly ash (common in Colorado to address alkali-silica reactivity or sulfate attack concerns).

The 5.75-sack mix (540 lb cementitious/cu yd concrete) had a water-to-cementitious ratio (w/cm) of 0.34. Both ASTM C150 Type I/II and ASTM C1157 GU cements were trial-batched in the laboratory and achieved similar plastic and hardened properties. CDOT Class P requires 4,200-psi compressive strength

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at 28 days or the performance option of 650-psi 28-day flexural strength. The cement proved to be consistent and helped contribute to the achievement of the quality performance incentive per CDOT standards by achieving an average 28-day flexural strength of 695 psi. Most of the paving was completed during hot summer months of 100°F-plus ambient air temperatures, and hot-weather concrete practices were followed. Workers did not notice a difference between the widely used ASTM C150 Type I/II cement and the “new and green” ASTM C1157 GU cement.

Since then, CDOT has used this ASTM C1157 GU cement on a number of projects, including an I-25 construction project 20 miles south of Denver that connects Denver and Colorado Springs. Interstate Highway Construction completed the concrete paving on this project in several phases, starting in August 2008 and completing construction in October 2009. The project was a 12.5-in.-thick doweled JPCP with 15-ft joint spacing. A CDOT Class P concrete (5.5-sack mixture [517 lb cementitious/cu yd] with a 0.42 w/cm) containing Holcim’s Portland Plant ASTM C1157 GU cement and 20% Class F fly ash was used throughout, achieving an average 28-day flexural strength of 710 psi. Jeff Klemick, a project engineer for PBS&J, commented that he was impressed with the high quality of concrete on this project with no reported problems.

The Utah Department of Transportation (UDOT) has accepted ASTM C1157 cements for many years but until 2008 did not allow the addition of fly ash to an ASTM C1157 GU cement at a concrete batch plant. One of the first projects to use the ASTM C1157 GU cement in Utah was the Lost Creek Road, which is the major transportation route for Holcim’s Devil’s Slide Plant. This pavement is exposed to heavy loads from cement bulk carriers and raw material delivery trucks. The canyon and river convergence posed a variety of construction issues and ultimately required hand placement of the ready-mix concrete made with Devil’s Slide ASTM C1157 GU portland-limestone cement and 20% Class F fly ash.

Concrete was batched and transported 30 miles to the jobsite where construction crews placed 3,000 cu yd of 10-in. JRCP. The average 28-day compressive strength was 5,120 psi, and the average flexural strength was 720 psi.

Another project was constructed in Utah as part of a recent pooled-fund study with 10 DOTs and the FHWA, titled Development of Performance Properties of Ternary Mixtures. The University of Utah and UDOT performed a trial of a ternary mixture on a reconstruction project of a major east/west corridor in Salt Lake City. The ternary mixture utilized Devil’s Slide ASTM C1157 GU cement and 25% Class F fly ash. The trial consisted of a single day’s placement using the ternary mixture. The concrete was tested and compared with a control mixture made with ASTM C150 Type II/V cement and 25% Class F fly ash used on the bulk of the project. The contractor did not notice any difference between the ternary mixture and
the control, and the University of Utah has monitored the project and has not seen any cracking or other defects in the placement. Average 28-day compressive strengths for the ternary mix were above 5,000 psi, which exceeded the design strength of 4,000 psi.

Easy on the cement
As sustainability increases in importance in the design and construction of transportation infrastructure, approaches to reduce the environmental footprint of concrete become more attractive. Since concrete is the most commonly used construction material on the planet, it has a large environmental footprint. In particular, the portland cement in typical concrete is responsible for roughly 95% of CO₂. In the U.S., the production of portland cement is responsible for 1.5 to 2% of the nation’s CO₂ emissions, whereas globally cement production is responsible for roughly 5% of worldwide CO₂ emissions.

One key to reducing the carbon footprint of concrete infrastructure is to reduce the amount of portland cement used. This can be accomplished through better design and longevity, resulting in less concrete being needed, reducing the amount of portland cement in a cubic yard of concrete and/or by using alternative, lower CO₂-producing cement binders. ASTM C1157 performance-specified cements are relatively new to the market, but offer an excellent opportunity to reduce the environmental footprint of concrete. Since the binder must only meet certain physical performance test requirements, innovative strategies to achieve performance objectives can be explored including intergrinding with limestone and/or intergrinding or blending SCMs such as fly ash and slag cement.

Test results have shown that the ASTM C1157 GU portland-limestone cements produced at Holcim’s Portland Plant and Devil’s Slide Plant have similar or improved properties compared with the plants’ ASTM C150 portland cements. These properties include typical fresh concrete behavior, the ability to blend with Class F fly ash to mitigate alkali-silica reactivity and sulfate resistance, freeze-thaw resistance, resistance to deicer scaling, acceptable drying shrinkage and rapid chloride permeability, and excellent compressive strength values. A limited number of DOTs are taking advantage of using ASTM C1157 cements including Colorado and Utah, where projects have demonstrated that hand-placed and slipform paving concrete made with ASTM C1157 GU cement are readily constructable and can easily achieve specified strength requirements. These cements were used in mixtures that also contained fly ash, demonstrating their versatility. In other words, they appear to perform similarly to ordinary portland cement with a reduced environmental footprint, an extraordinary advantage as we strive to improve the sustainability of transportation infrastructure.

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