USE OF PERFORMANCE SPECIFIED (ASTM C1157) CEMENTS IN COLORADO TRANSPORTATION PROJECTS: CASE STUDIES

First Author: Thomas J. Van Dam, Ph.D., P.E. LEED AP, Program Director, Applied Pavement Technology, Inc., 200 Michigan St., Suite 321, Hancock, MI, 906-487-7454, tvandam@appliedpavement.com (Corresponding Author)

Second Author: Brooke W. Smartz, LEED AP, Manager, Sustainable Products, Mountain Sales Group, Holcim (US) Inc., 303.926.3749, Brooke.Smartz@Holcim.com

Word Count
Text: 3,754
Figures (1 @ 250 each) = 250
Total: 4,004

November 13, 2009
ABSTRACT
As sustainability becomes an increasingly important element in the design and construction of transportation infrastructure, approaches to reduce the environmental footprint of concrete become more attractive. Concrete, as the most widely used construction material on the planet, has a significant environmental impact. Although portland cement is a relatively minor constituent by volume, its presence can significantly contribute to the CO2 associated with concrete. A key to reducing the carbon footprint of concrete is to reduce the amount of portland cement used. One way to accomplish this is by using alternative cement binders. ASTM C1157 performance specified cements are relatively new to the market, having no chemical or physical requirements other than they must meet certain physical performance test requirements. Colorado is one of five state departments of transportation (DOTs) that allow the use of ASTM C1157 cements. Three case studies are presented to demonstrate that slipform paving concrete made with ASTM C1157 cement are readily constructible and can easily achieve specified short-term performance requirements. These cements were used in mixtures that also contained fly ash demonstrating their versatility. Due to the newness of the specification, there is limited long-term field performance data.

INTRODUCTION
Sustainability, and sustainable design, continues to increase in importance as resources grow scarcer, the cost of energy increases, and environmental stewardship is integrated into all elements of transportation design and construction. Due to its relatively low cost, local availability, versatility, and hallmark longevity, portland cement concrete is the most widely used building material on the planet, with approximately a cubic yard (4,000 lbs) of concrete used annually for every person on Earth. In transportation structures, concrete is used for foundations, hydraulic structures, bridges, retaining walls, barriers, pavements, curb and gutter, and sidewalks. In fact, without concrete, it is difficult to envision how our modern transportation system could exist. But this popularity comes with an environmental price tag. It is recognized that the material acquisition, transportation, and processing inherent in delivering concrete to the job site has a significant environmental impact including use of non-renewable resources, land-use issues arising from raw material acquisition, and of increasing importance, production of gases associated with global climate change.

This paper will discuss the recent introduction of performance specified (ASTM C1157) cements in the U.S. market and how the use of these cements can have a dramatic impact in reducing the environmental impact of concrete used in transportation structures. Case studies based on the experience of the Colorado Department of Transportation (CDOT) are used to illustrate that these cements are viable for large scale use by transportation agencies throughout the country.

BACKGROUND
Concrete is a mixture of graded aggregates (naturally-derived stone and sand, recycled concrete, and/or industrial byproducts such as air-cooled blast furnace slag) held together by glue made from cement and water. Air is entrapped in the paste and may also be purposely entrained to enhance resistance to freezing and thawing. When mixed together, the fresh concrete is plastic and will readily flow under vibration. This allows mixing, transportation, placement, and consolidation into the desired ultimate shape. A chemical reaction between the cement and...
water, called hydration, transforms the fluid paste into a solid, firmly binding the aggregates together into a rock-like mass that we know as concrete.

The aggregates typically occupy between 60 to 75 percent, the air 4 to 8 percent, and the water 14 to 21 percent of the absolute volume of the concrete (Kosmatka et al. 2008). At the time of mixing, the cement (which traditionally has been an ASTM C150 specified portland cement) is between 7 and 15 percent of the volume of the concrete. In addition to portland cement, supplementary cementitious materials (SCMs), including industrial byproducts such as fly ash obtained from burning coal in power plants and ground granulated slag produced from iron blast furnaces, have been added to the concrete either at the concrete plant or blended by the cement manufacturer. In the latter case, these cements are produced and sold in compliance with ASTM C595 as blended cements.

The reason that portland cement is so critical from an environmental perspective is that roughly 1.5 to 2.0 percent of the U.S.’s anthropogenic (derived from human activity) CO2 is produced in the manufacturing of portland cement. Globally portland cement manufacturing produces approximately 5 percent of the world’s CO2 output (PCA 2009). Further, it is portland cement that is responsible for approximately 95 percent of all CO2 associated with concrete typically used by transportation agencies (Marceau et al. 2007). Thus efforts are underway to reduce the amount of portland cement used worldwide, including constructing longer-lasting structures, reducing the cement content of concrete by increasing the volume of aggregate, and using cementitious materials that contain a larger volume of non-portland cement binder (Mehta 2002, Van Dam and Taylor 2009). This last strategy is one embraced by the World’s cement manufactures and is the focus of this paper.

Cement and CO2
There are two primary sources of CO2 inherent in the manufacturing of portland cement. The first, which is responsible for roughly 40 percent of the CO2 generated, is the burning of fossil fuels needed to acquire and prepare raw materials, pyroprocess the raw materials to induce the chemical transformations necessary to create portland cement, and grinding of the clinker after kilning. This requires that the raw materials reach a temperature of 2700 °F in a rotary kiln. The heat is generated from burning various fuels, including discarded tires, waste fuels, and even biomass fuels, but the predominant source of fuel is coal. The second source of CO2, which is responsible for almost 60 percent of that generated, is from the predominant raw material: limestone or calcium carbonate (CaCO3). As the limestone is heated it undergoes a process called calcination characterized by the liberation of CO2 leaving calcium oxide (CaO). The CaO subsequently reacts with silica at the higher kiln temperatures to form calcium silicates, which are the primary cementing compounds found in portland cement. The end product from the cement kiln is clinker, which are small dark nodules.

As illustrated in Figure 1, on average the “clinker factor” is about 0.96 tons of CO2 associated with the production of 1.0 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, through the use of dry kilns versus wet kilns and the utilization of preheaters and precalciners. But even the most efficient cement kilns still have a clinker factor in the high 0.80’s to low 0.90’s since there are
limits to the minimum amount of fuel required to obtain temperatures necessary for clinkering and it is impossible to change the amount of CO\textsubscript{2} liberated from CaCO\textsubscript{3} due to calcination.

The next step in 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 CO\textsubscript{2} is generated in this processing, the CO\textsubscript{2} per ton of cement is reduced to 0.92 tons as the clinker is diluted 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).

Recently, this strategy of diluting 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, but recent modifications to ASTM C150 (and AASHTO M 85) have allowed up to 5 percent 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 (Mataschei et al. 2007). Unquestionably such additions have a significant environmental benefit as the replacement of clinker with limestone (or any other material) directly reduces the CO\textsubscript{2} associated with the cement.

As illustrated in Figure 1, composite cements can also be created that can reduce the CO\textsubscript{2} associated with the cement by 50 percent or more. Cements interground or blended with a pozzolan (P), ground slag (S), and most recently a ternary (T) combination of SCMs are

<table>
<thead>
<tr>
<th>Cement Clink</th>
<th>Cement Grinding &amp; Blending</th>
<th>Cement</th>
<th>Impact of Cement Content and SCMs on CO2 per Cubic Yard of Concrete</th>
<th>Impact of Cement Content and SCMs on CO2 per Cubic Yard of Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.92 t CO2 per t cement</td>
<td>Cement: ASTM C 150</td>
<td>Cement, 0.65 to 0.80 t CO2 per t cement</td>
<td>% SCM</td>
<td>CO2 Bcyl\textsuperscript{d}</td>
</tr>
<tr>
<td>564</td>
<td>0</td>
<td>527</td>
<td>470</td>
<td>0</td>
</tr>
</tbody>
</table>
available, specified under ASTM C595 (AASHTO M 240). These are classified as Type IP(X),
Type IS(Y), and Type IT (PX)(SY) respectively, where “X” and “Y” denote the targeted percent
replacement of each. Typical replacement rates for blended cements are 15 to 25 percent for
Type IP(X) and 30 to 50 percent for Type IS(X). A Type IT might have 15 to 30 percent slag
and 10 to 20 percent pozzolan, although these can vary substantially depending on the materials.
They can be further designated with “A”, “MS” or “HS”, or “MH” or “LH”, indicating air
entraining, moderate or high sulfate-resistance, or moderate or low heat of hydration,
respectively. In practice, it is common to blend cement with SCMs at the concrete plant where
fly ash or slag cement is added to the mix in addition to portland cement. Although this is viable
and provides the concrete producer with flexibility to vary the rate of replacement from batch to
batch, it does have some shortcomings. For one, the use of ASTM C595 blended cement will
eliminate the potential for proportioning mistakes that can occur in the field. Also, changes in
either the cement or SCM can have a significant impact on concrete properties, which if it occurs
in the middle of a job can cause problems in the field. In contrast, cement manufactures can
carefully monitor and control the physical and chemical properties of the final product, and thus
it can be delivered with great consistency. This will assist in avoiding incompatibilities that can
occur with other concrete constituents such as chemical admixtures (Taylor et al. 2007).

The recent adoption of performance-based standards (the first version of ASTM C1157 appeared
in 1998 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,
Type MS and HS cements use ASTM C1012, Standard Test Method for Length Change of
Hydraulic-Cement Mortars Exposed to a Sulfate Solution, to ensure resistance to sulfate attack.
The performance classification of hydraulic cement is thus based on the concept material
performance is of interest, not its composition. This approach promotes innovative development
of composite portland cements (portland cement blended with multiple SCMs and/or limestone)
as well as opening the door to non-portland cement binders that have the potential to
significantly alter 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 five state
departments of transportation (Colorado, Michigan, Montana, New Mexico, and Utah) accept
their use for transportation projects. Other states are currently investigating adoption of the
ASTM standard as there isn’t an equivalent AASHTO specification. The remainder of this paper
will present three case studies from Colorado showing the successful use of ASTM C1157
performance specified hydraulic cement in transportation projects.

CASE STUDIES
The following case studies are all from Colorado and feature the use of an ASTM C1157 GU/MS
cement produced at the Holcim Portland Plant located in Florence, Colorado. The projects
include pavement construction on local roads, a rural state highway, and a section of major
The impetus for the use of these cements has been local and statewide efforts to address environmental concerns and lower the carbon footprint of infrastructure. Denver, for example, instituted a city-wide action plan called Greenprint Denver to promote the importance of sustainable development and ecologically-friendly practices throughout the community. Greenprint recognized that concrete contributed to the city’s carbon footprint and recommended the use of fly ash and other strategies in concrete pavement to reduce this footprint, providing opportunities for the acceptance of ASTM C1157 cement. Case Study #1 features the 40th Avenue project in Denver in response to the Greenprint initiative. The Colorado Department of Transportation (CDOT) has allowed ASTM C1157 cement in their specifications for over a decade, yet due to another stipulation in the specifications that forbid the use of fly ash with a “blended” cement, ASTM C1157 cements were not used. In the last year, the CDOT specification was revised to allow ASTM C1157 cements containing up to 10 percent limestone to be used with fly ash added at the concrete plant. This new specification aligns with the state’s Climate Action Plan to lower the environmental impact of construction. Case Studies #2 and #3 feature CDOT projects made with ASTM C1157 cement. Eric Prieve, CDOT Concrete and Physical Properties Engineer sums it up, stating, “Using ASTM C1157 cements allows CDOT to reduce greenhouse gas emissions in the construction of concrete pavements with no compromise in quality and long-term performance.”

ASTM C1157 cements have been supplied with 10 percent limestone in Colorado since around 2006 by two suppliers. Holcim’s ASTM C1157 cement was developed to perform similar to the ASTM C150 Type I/II cement most commonly used, but with lower environmental impact. Cement and concrete testing was performed above and beyond what is required by ASTM C1157 which includes freeze-thaw (ASTM C666), deicer scaling (ASTM C672), shrinkage (ASTM C157), permeability (ASTM C1202), compressive strength (ASTM C39), and ASR mitigation (ASTM C1260 and 1567) to compare the performance of ASTM C150 Type I/II and C1157 GU cements. In general, the results were comparable in the harsh durability tests comparing various cement and fly ash combinations. Results are available for discussion and review outside of this paper.

**Case Study #1: 40th Avenue, Denver, CO**

This project was constructed in 2007 on the former site of Stapleton Airport in Denver, 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 six million tons of aggregate used in new concrete in one of the world’s largest concrete recycling projects (Concrete Producer 2004). In support of increasing the sustainability of the newly constructed plain jointed concrete pavement, the 40th Avenue and Havana construction project used ASTM C1157 cement and 20 percent Class C fly ash along with recycled concrete aggregates. The mix was designed with 7 percent 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 1, 2, 3, and 7 days, respectively. The 7-day flexural strength was 825 psi. Note these are higher strengths than specified or structurally needed for PCCP, but field adjustments, later shown to be unnecessary, were made to compensate for the cold weather placement conditions.
The contractor placed a previous section of roadway in this development using a similar mix design, but with an ASTM C150 Type I/II cement. Quality control and field personnel did not notice any unusual batching or field placement changes between the C150 and C1157 mix designs. This project also serves as a potential side by side field durability study. The sections of pavement have been through two winters to date with no observable differences in performance.

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 Paving Association in 2008.

**Case Study #2: US HWY 287, Lamar, CO**

This CDOT project is a rural highway constructed on US HWY 287 near Lamar, CO. Highway 287 is part of the Ports to Plains US Highway route that accommodates heavy truck traffic connecting commerce between Mexico and the United States. Castle Rock Construction was the contractor for this $17.3 million dollar construction project that reconstructed 7 miles of highway in concrete and widened the shoulders. The project also included minor bridge work, new concrete box culverts, embankment improvements, signing and striping. The project was constructed in two phases starting in May 2008 and finishing in June 2009. This concrete project used innovative traffic control techniques with a successful pilot car operation to shuttle one lane of traffic through the work zone while keeping delays often less than 10 minutes. This is the first CDOT project in Colorado and across the United States to utilize ASTM C1157 10 percent limestone cement.

The 7-mile jointed plain concrete pavement used a CDOT Class P mixture with ASTM C1157 cement and 20 percent Class F fly ash (common in Colorado to address alkali-silica reactivity and/or sulfate attack concerns). The 5.75 sack mix (540 lbs cementitious/yd³ concrete) had a relatively low water-to-cementitious ratio of 0.34. Both Type I/II and C1157 cements were trial batched in the laboratory and achieved similar plastic and hardened properties. CDOT Class P requires 4,200 psi at 28 days or the performance option of 650 psi flexural. The concrete mix contained water-reducing and air-entraining admixtures. The average 28-day flexural strength was 695 psi. The cement proved to be consistent and helped contribute to the achievement of the quality performance incentive per CDOT standards. Most of this paving was completed during hot summer months of 100 oF plus temperatures and hot weather concrete practices were followed. Workers did not notice a difference between the widely used Type I/II cement and the “new and green” C1157 cement.

**Case Study #3: I-25, Castle Rock, CO**

This I-25 construction project is on a major corridor 20 miles south of Denver that connects Denver and Colorado Springs. Interstate Highway Construction was awarded the concrete paving in this reconstruction project. The project was designed as a 12.5-in doweled jointed plain concrete pavement with 15-ft joint spacing. A CDOT Class P concrete mixture containing ASTM C1157 cement and 20 percent Class F fly ash was used throughout. The concrete mix is a 5.5 sack mix (517 lbs cementitious/yd³), 0.42 w/c, that contains Euclid paving admixtures. The average 28-day flexural strength was 710 psi. The rigorous QC/QA program reports positive
results to date. Jeff Klemick, a project engineer for PBS&J, commented that he is impressed with the high quality of concrete on this project with no reported problems. This project was done in several complex phases starting in August of 2008. In July of 2008 an open house was held to educate local engineers on the performance and environmental benefits of concrete containing ASTM C1157 cements. The final phase of this project was completed in October of 2009.

SUMMARY

As sustainability becomes an increasingly important element in the design and construction of transportation infrastructure, approaches to reduce the environmental footprint of concrete become more attractive. The following was presented in this paper:

- Concrete is the most commonly used construction material on the planet. Although portland cement is a relatively minor constituent by volume, its presence is responsible for the vast majority of CO2 associated with concrete. In the U.S., the production of portland cement is responsible for 1.5 to 2.0 percent of the nation’s CO2 emissions; globally, cement production is responsible for 5 percent of world-wide CO2 emissions.

- The 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 cement binders.

- ASTM C1157 performance specified cements are relatively new to the market. There are no chemical or physical requirements for the binder other than they must meet certain physical performance test requirements. As such, innovative strategies to achieve performance objectives can be explored including intergrinding with limestone and intergrinding or blending SCMs such as fly ash and slag cement.

- Five state DOTs allow the use of ASTM C1157 cements including Colorado. Environmental initiatives in Colorado have created an opportunity to demonstrate the applicability of these cements. Three case studies are presented show that slipform paving concrete made with ASTM C1157 cement are readily constructible and can easily achieve specified strength requirements. These cements were used in mixtures that also contained fly ash demonstrating their versatility. Due to the newness of the specification, there is limited long-term field performance data.

ACKNOWLEDGEMENTS

Appreciation is extended to the Colorado Department of Transportation for their commitment to using innovative technologies to improve sustainability and willingness to share their experiences.

REFERENCES


