Equivalent Performance with Half the Clinker Content using PLC and SCM

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Abstract

In response to growing pressures to reduce the clinker content in cement, the Canadian Standards Association (CSA A3001-08) introduced a new classification of cement in 2008, this being Portland Limestone Cement (PLC) containing up to 15% limestone. This paper presents data from laboratory and field studies on the properties of concrete produced with portland limestone cement (PLC) and moderate to high levels of supplementary cementing materials (SCM). The test data indicate that PLC with up to 15% limestone can be manufactured to produce equivalent performance to a portland cement (PC) in terms of concrete strength and other properties, including durability. The equivalent performance is achieved by optimizing the PLC with regards to composition and particle-size distribution, and requires intergrinding rather than blending of the portland cement and limestone. The performance of concrete produced with PLC in combination with a wide range of SCM is also equivalent to that of concrete produced with PC and the same SCM. Full-scale field trials have been conducted with concretes with blends of PLC and SCM and these concretes provide similar or improved performance compared to PC concrete; in one case the clinker content represented less than 50% of the total cementitious material. A clinker reduction of 50% represents a very significant reduction in the carbon footprint associated with the production of portland cement clinker.

Introduction

In 1990, in response to growing pressures to increase the sustainability of concrete construction, a number of major cement companies pledged to reduce the emissions associated with the production of cement by 20% by the year 2010. The calcination of limestone is an inevitable process in the production of portland cement clinker and so cement companies are
striving to reduce the CO₂ footprint by making the process more energy efficient and by reducing
the clinker content of the cement.

Portland limestone cement is produced by blending portland cement and limestone or,
preferably, intergrinding portland cement clinker, limestone and calcium sulfate. Such cements
have been in use in Europe for decades and in 2004 more than one third of the cement produced
in the European Community were CEM II Portland-Limestone or Portland-Composite Cement
which may contain up to 35% limestone (Herford, 2009). In Canada, the incorporation of up to
5% limestone has been permitted in portland cements since 1983. Twenty years later ASTM
finally allowed the use of the same amount of limestone in ASTM C 150 portland cements in
2004 with AASHTO M85 following suit in 2007. In response to growing pressures to reduce the
clinker content in cement, the Canadian Standards Association (CSA A3001-08) introduced a
new classification of cement in 2008, this being Portland Limestone Cement (PLC) containing
up to 15% limestone. Limestone can be used up to this level in all types of cement except for
sulfate-resisting cements. In 2009, CSA permitted the use of PLC in all classes of concrete
except for sulfate-exposure classes (CSA A23.1-09).

Considerable laboratory testing has been conducted in Canada in recent years to
demonstrate that PLC with up to 15% limestone can be manufactured to produce equivalent
performance to a portland cement in terms of concrete strength and other properties, including
durability. The equivalent performance is achieved by optimizing the PLC with regards to
composition and particle-size distribution, and requires intergrinding rather than blending of the
portland cement and limestone. This paper presents data from the laboratory testing of concrete
manufactured using portland cement (PC) and portland limestone cement (PLC) produced from
the same clinker at the same plant. Concrete was also produced with and without supplementary
cementing materials (SCM) and at various water-to-cementitious-material ratios (W/CM).

Effect of Fineness and Limestone Quality

Figure 1 shows compressive strength data for concrete (W/CM = 0.49 to 0.51) produced
with PLC (12% limestone) at a range of different Blaine values (surface area) using limestone
consisting of either 92% or 80% CaCO₃; the strength data are presented as a percentage of the
control concrete produced with PC with a surface area of 380 m²/kg. These data and data from
other trials indicate that the Blaine has to be increased by 100 to 120 m²/kg for the PLC to
achieve equivalent performance in terms of strength at 7 to 28 days. The 1-day strength of PLC
concrete may be increased compared to equivalent PC concrete as the very fine limestone
particles act as nucleation sites for cement hydration products thereby increasing the rate of
cement hydration (Soroka and Setter, 1977; Bonavetti et al, 2003). Within the range evaluated,
the calcium carbonate of the limestone does not appear to affect the concrete strength. CSA
A3001-08 requires that limestone used for the manufacture of PLC must have a minimum
CaCO₃ content of 75% (by mass). There is also a requirement that the methylene blue value, an
indication of clay content, shall not exceed 1.2 g/100 g (determined by test method CSA A3004-D1).

![Effect of Surface Area (Blaine) and Purity of Limestone on the Strength of Concrete](image)

Figure 1 Effect of Surface Area (Blaine) and Purity of Limestone on the Strength of Concrete (W/CM = 0.49 to 0.51) Produced with PLC (Strength expressed as a percentage of control concrete produced with PC with a Blaine value of 380 m²/kg)

### Effect of Intergrinding PLC

Figure 2a shows the particle size distribution of PLC and PC ground to produce equivalent performance when used in concrete. As discussed above, PLC has to be ground to higher fineness to achieve equivalent performance. Figure 2b shows the particle size distribution of the clinker and limestone in the PLC cement. This distribution was calculated using the results from laser particle analysis and chemical analysis to determine the limestone content of different size fractions. It can be seen that the softer limestone is ground to a significantly finer particle size than the harder clinker particles when the two materials are interground. Testing has generally indicated improved performance of PLC when the limestone and clinker are interground as opposed to simply blending finely-ground limestone with portland cement. The clinker in the PLC is also finer than the clinker in the PC.
A series of concrete mixtures were produced at a range of W/CM with PC and PLC (12% limestone) produced from the same clinker. The PLC was ground to higher Blaine to achieve equivalent performance. Concrete mixes were also produced with fly ash and slag. Details of the cementing materials and the concrete mixtures are shown, respectively, in Tables 1 and 2.

### Table 1 Chemical Composition of Cementing Materials

<table>
<thead>
<tr>
<th></th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>CaO</th>
<th>MgO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>SO$_3$</th>
<th>LOI</th>
<th>Blaine (m$^2$/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>20.34</td>
<td>5.30</td>
<td>1.94</td>
<td>62.50</td>
<td>1.72</td>
<td>0.11</td>
<td>1.14</td>
<td>4.14</td>
<td>2.65</td>
<td>366</td>
</tr>
<tr>
<td>PLC</td>
<td>19.75</td>
<td>5.19</td>
<td>1.88</td>
<td>61.25</td>
<td>1.66</td>
<td>0.10</td>
<td>1.18</td>
<td>3.90</td>
<td>4.83</td>
<td>520</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>53.98</td>
<td>23.52</td>
<td>3.82</td>
<td>11.66</td>
<td>1.27</td>
<td>3.08</td>
<td>0.69</td>
<td>0.22</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>Slag</td>
<td>36.84</td>
<td>10.15</td>
<td>0.53</td>
<td>36.41</td>
<td>12.92</td>
<td>0.42</td>
<td>0.62</td>
<td>3.63</td>
<td>-1.27</td>
<td></td>
</tr>
</tbody>
</table>

Air-entraining admixture (AEA) was added to mix series B and C to achieve a target air content of 5 to 7%. Mixes with PLC required slightly more AEA than mixes with PC. A normal range water-reducing admixture (ASTM C494 Type B) was added to all mixes at a dosage of 3 fl. oz/cwt (180 mL/100kg). A high-range water-reducing admixture (sulfonated naphthalene-formaldehyde) was added where required to raise the slump to the target level of 4 to 5 in. (100 to 125 mm). There was no noticeable difference between PC and PLC concretes in terms of workability, placing or finishing characteristics. However, the mixes without SCM in mix series
A and B did show reduced bleeding with PLC compared with PC. No bleed water was observed for mixes with SCM and mixes in series C.

### Table 2 Concrete Mix Proportions, lb/yd³ (kg/m³), Air Content, %, and Slump, in. (mm)

<table>
<thead>
<tr>
<th></th>
<th>Series A</th>
<th></th>
<th></th>
<th>Series B</th>
<th></th>
<th></th>
<th>Series C</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>W/CM</td>
<td>0.78</td>
<td>0.80</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>0.40</td>
</tr>
<tr>
<td>PC</td>
<td>396 (235)</td>
<td>-</td>
<td>597 (354)</td>
<td>-</td>
<td>388 (230)</td>
<td>-</td>
<td>482 (286)</td>
<td>-</td>
<td>689 (409)</td>
</tr>
<tr>
<td>PLC</td>
<td>-</td>
<td>396 (235)</td>
<td>-</td>
<td>603 (358)</td>
<td>-</td>
<td>389 (231)</td>
<td>-</td>
<td>484 (287)</td>
<td>-</td>
</tr>
<tr>
<td>Slag</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>211 (125)</td>
<td>211 (125)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>121 (72)</td>
<td>120 (71)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Water</td>
<td>310 (184)</td>
<td>317 (188)</td>
<td>268 (159)</td>
<td>271 (161)</td>
<td>270 (160)</td>
<td>270 (160)</td>
<td>271 (161)</td>
<td>271 (161)</td>
<td>276 (164)</td>
</tr>
<tr>
<td>Air</td>
<td>1.5</td>
<td>1.4</td>
<td>6.2</td>
<td>5.3</td>
<td>6.0</td>
<td>5.6</td>
<td>5.2</td>
<td>5.0</td>
<td>6.2</td>
</tr>
<tr>
<td>Slump</td>
<td>4.75 (120)</td>
<td>4.50 (115)</td>
<td>4.75 (120)</td>
<td>4.75 (120)</td>
<td>4.25 (110)</td>
<td>4.25 (110)</td>
<td>5.00 (130)</td>
<td>4.25 (110)</td>
<td>5.00 (130)</td>
</tr>
<tr>
<td>Set time (h:m)</td>
<td>5:40</td>
<td>5:10</td>
<td>5:40</td>
<td>4:50</td>
<td>6:20</td>
<td>5:45</td>
<td>7:05</td>
<td>5:45</td>
<td>6:35</td>
</tr>
</tbody>
</table>

Concrete mixes with PLC set more quickly (by about 30 to 45 minutes) than similar mixes with PC (see Table 2).

Figure 3 shows the compressive strength results for concretes from mix series A (W/CM = 0.78 to 0.80) and C (W/CM = 0.40). There is no significant difference between the strength of PC and PLC concretes at any age for mix series A. For mix series C, the concrete produced with PLC has a slightly higher strength (4 to 9%) than the concrete produced with PC at all ages. Figure 4 shows the compressive strength results for mix series B (W/CM = 0.45). In all but one case (20% fly ash at 56 days) the compressive strength was higher for the concrete with PLC compared with the same concrete with PC. This is particularly noticeable at 1 day as PLC concretes have on average 20% greater strength than the PC concretes.

Figure 5 shows results of rapid chloride permeability tests (RCPT) conducted in accordance with ASTM C 1202. As expected, the charge passed decreases for the concrete without SCM as the W/CM decreases, and significant reductions in the charge passed are observed for concrete containing fly ash or slag, especially at 56 days. It is clear from the data in Figure 5, that use of PLC instead of PC has no significant impact on the result from this test.

Figure 6 shows results from (a) deicer-salt scaling tests (ASTM C 672) and (b) freeze-thaw tests (ASTM C 666). The mass loss after 50 cycles increases with SCM content, however, values are still below performance limits frequently used in Canada (~ 30 oz/yd², 1000 g/m²).
Figure 3 Compressive Strength Results for PC and PLC Concrete (W/CM = 0.78-0.80 and 0.40)

Figure 4 Compressive Strength Results for PC and PLC Concrete (W/CM = 0.45) with and without Fly Ash and Slag
Figure 5 Results from Rapid Chloride Permeability Tests (ASTM C 1202)

Figure 6 Results from (a) Deicer Salt Scaling Tests (ASTM C672) and (b) Freeze-Thaw Tests ASTM C666 Procedure A)
There appears to be no consistent effect of limestone on the performance of the concrete in the scaling test. The mass loss is increased for the PLC concrete compared to the PC concrete for mixes with fly ash whereas the opposite is the case for mixes with slag. All of the concrete mixes performed well in the cyclic freeze-thaw test (ASTM C 666) with durability factors in the range of 98 to 102%.

Figure 7 shows the expansion of mortar bars and concrete prisms containing an alkali-silica reactive aggregate (siliceous limestone from the Spratt quarry in Ontario). Expansion results are reported at 14 days for the accelerated mortar bar test, AMBT (ASTM C 1260), 1 year for the concrete prism test, CPT (ASTM C 1293) and 3 months for the accelerated concrete prism test, ACPT (this test is similar to the CPT except specimens are stored at 140°F, 60°C). The data show that there is no consistency difference between expansions produced with PC compared with PLC.

Figure 8 shows the expansion of mortar bars tested in accordance with ASTM C 1012 (mortar bars stored in 5% Na₂SO₄). Both PC and PLC fail to make the requirements for moderate sulfate resistance (expansion ≤ 0.10% at 6 months) and broke before the 12-month reading. These cements are not expected to be sulfate resistant as the C₃A content of the clinker is 11%.

**Field Trials with PLC**

The first field trial was conducted using PLC with 12% interground limestone produced in Lafarge’s Bath cement plant in Ontario. A total of eight concrete mixtures were produced, four with PLC and four with PC from the same plant. A blended SCM (2 parts slag and 1 part fly
ash) was added at the ready mix plant at cement replacement levels of 0, 25, 40 and 50%. The concrete was used to construct a parking slab (4500 ft², 450 m²) at the ready mix plant. The concrete was placed on October 6, 2008. Extensive laboratory testing was conducted on specimens cast during the placing of the concrete and the results were recently reported in a paper by Thomas et al (2010). The results of the testing are in general agreement with the results of the laboratory tests presented in this paper, however, significantly higher levels of SCM were used in this field trial. In the PLC mix with 50% SCM, the clinker only constituted approximately 41 to 42% of the total mass of cementing materials. This compares with about 91 to 92% clinker for the control mix produced with PC and no SCM (PC contains approximately 3 to 4% limestone and 5% gypsum).

The second field trial was conducted using PLC produced at Lafarge’s Exshaw cement plant in Alberta. The cement was produced by intergrinding 12% limestone. This trial also incorporated 4 concrete mixes with PLC and 4 with PC, with fly ash being added at the ready mix plant at levels of 0, 15, 25 and 30%. The concrete was used predominantly for paving (see Figure 9, but also for two retaining walls and a section of slipformed curb. The concrete was placed on September 10 and 11, 2009. Figure 9 also shows the strength of the concrete mixes at 11 days when the pavement was opened to traffic.

![Figure 9 Paving at Exshaw Plant in Alberta and Strength Results at 11 Days when the Roadway was opened to Traffic](image)

The third field trial was conducted using a blended portland limestone cement produced by intergrinding 12% limestone and 15% slag granules together with the portland cement clinker and gypsum at Lafarge’s Brookfield cement plant in Nova Scotia. The performance of this cement was compared with a similar blended portland cement produced with 15% slag. Six
concrete mixes were produced with these two cements, with fly ash being added at the ready mix plant at replacement levels of 0, 15 and 20% fly ash. The concrete was used to pave the roadway outside the main entrance of the cement plant and was placed on October 3, 2009. Figure 10 shows construction of the pavement and the strength of the six mixes at 3 days.

All three of these trials include concrete paving that will be subjected to frequent deicing salts and sand, heavy truck traffic, and severe winter conditions. These pavements will be inspected annually. In all three cases, extensive laboratory testing was performed during construction. Full details of the construction and the results of testing will be reported in a separate paper. Essentially the results from the field trials confirm that PLC with 12% limestone provides equivalent performance to PC. No noticeable differences were observed in the placing characteristics of similar concrete mixes produced with either PC or PLC, however, mixes with PLC appeared to have a higher paste content and were easier finish.

![Figure 10 Paving at Brookfield Plant in Nova Scotia and Strength Results at 3 Days](image)

### Summary

The laboratory tests indicate that equivalent performance in terms of strength and durability can be achieved with portland limestone cement containing 12% limestone interground with the cement clinker (and gypsum). This is confirmed by similar studies conducted by other cement companies in Canada. PLC was successfully used in three field trials across Canada. The field trials demonstrated that in certain applications it is possible to produce concrete where the clinker content represents less than 50% of the total cementing materials.

It should be noted that the equivalent performance measured for PLC in this study was obtained by intergrinding the limestone with the clinker and producing a finished cement with a
Blaine that is 100 to 120 kg/m² higher than the equivalent PC produced from the same clinker with lower amounts of limestone (3.5% limestone is typical for a portland cement in Canada). In such a cement the softer limestone will grind much finer than the clinker particles. It is believed that this helps with particle packing and increases the role of the limestone in terms or providing nucleation sites for the cement hydration products and, possibly, improving the distribution of the hydration products. In addition, very finely ground limestone is not completely inert as the CaCO₃ will react with the aluminate phases to produce calcium mono- (and hemi-) carboaluminate (Bonavetti et al 2001). The extent of this reaction is expected to increase as the fineness of the limestone increases and when additional alumina is available from fly ash and slag.

In Canada portland cements are permitted to contain up to 5% interground limestone, however, in most cases the amount is limited to about 3.5% because of LOI limits. Portland limestone cements are permitted to contain up to 15% limestone and it has been demonstrated that at least 12% can be included without jeopardizing performance. The adoption of PLC with 12 to 15% limestone instead of PC equates to a reduction in clinker of between 8 to 11%. This reduction in clinker leads to an equal reduction in the CO₂ emissions associated with the production of the cement.

The sulfate resistance of concrete produced with PLC is currently under investigation at a number of research laboratories in Canada. Until strategies for ensuring the sulfate resistance of PLC concrete are proven, concrete produced with PLC will not be permitted for use in sulfate exposure classes.

References