Concrete limestone cement (PLC) is produced by blending portland cement and limestone or intergrinding portland cement clinker, limestone, and calcium sulfate. Replacement of portland cement with limestone results in a proportionate reduction in the amount of CO₂ associated with concrete production, and this reduction can be further enhanced through the use of supplementary cementitious materials (SCMs) such as slag cement or fly ash. PLCs can, therefore, significantly minimize the concrete industry’s carbon footprint.

PLCs have been used in Europe for decades. Currently, European Committee for Standardization (CEN) Standard EN 197-1 allows CEM II portland-limestone cement or CEM II portland-composite cement to contain up to 35% limestone replacement levels. Canadian Standards Association (CSA) Standard A3001 has allowed the incorporation of up to 5% limestone in portland cement since 1983. In the U.S., ASTM C150 began allowing the use of up to 5% limestone in portland cements in 2004, and AASHTO M85 followed suit in 2007.

In 2008, CSA responded to growing pressures to further reduce the clinker content in cement by revising CSA A3001 to allow PLCs containing up to 15% limestone, and in 2009, CSA A23.1 was revised to permit the use of PLCs in all classes of concrete except sulfate-exposure classes.

Although limestone is often considered an inert filler when it is added to portland cement, it is not completely chemically inert and thus can contribute to the development of the concrete’s microstructure—particularly when interground with portland cement clinker. First, because limestone is softer than clinker, it will achieve a finer particle size when interground, producing an improved particle size distribution and improving particle packing. Secondly, the fine limestone particles act as nucleation sites, thereby increasing the rate of hydration of the calcium silicates at early ages and possibly improving the distribution of the hydrates. Finally, CaCO₃ will react chemically with aluminate phases to form carboaluminate phases. The extent of this reaction should increase as the fineness of the limestone increases and when PLCs are combined with slag cement or fly ash.

This article presents results from a recent demonstration of PLC concrete in the late-fall construction of a parking lot at a ready mixed concrete plant near Gatineau, QC, Canada. The performance of the plastic and hardened concretes produced with PLC at various levels of SCM replacement are compared with the performance of similar concrete mixtures produced with portland cement (PC) from the same cement plant.

**APPLICATION**

**Materials**

For our study, a CSA A3001 Type GU PC and a Type GUL PLC were used together with a blended SCM (currently marketed in Ontario and Quebec) that comprises two...
parts slag cement and one part fly ash, by mass. The PLC was produced by intergrinding limestone with calcium sulfate and the same clinker that was used to produce the PC; the limestone content of the finished PLC was 12%. The chemical composition of the cementitious materials is presented in Table 1.

### Production and placement

A total of eight concrete mixtures were batched at the ready mixed concrete plant. The total cementitious material content of each mixture was 355 kg/m³ (600 lb/yd³). Each batch contained either PC or PLC, and for each cement type, the SCM blend was used at replacement levels of 0, 25, 40, or 50%. The target air content was 6% and the target slump was 100 mm (4 in.). All mixtures contained a normal-range, water-reducing admixture. Details for mixtures are given in Table 2.

The concrete was used to construct a parking slab at the concrete plant on October 6, 2008. The slab area was about 450 m² (4500 ft²) (Fig. 1) and the thickness ranged from 150 to 200 mm (6 to 8 in.). The concretes were mixed in a truck mixer, placed by direct-chute discharge, consolidated with a hand-held vibratory screed, provided with a bull float and broom finish, and cured under insulated tarps for 1 day. During the day, the ambient

### Table 1: Composition of cementitious materials

<table>
<thead>
<tr>
<th>Cementitious material</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>SO₃</th>
<th>LOI, %</th>
<th>Blaine fineness, m²/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>20.53</td>
<td>4.63</td>
<td>2.77</td>
<td>62.7</td>
<td>2.48</td>
<td>0.21</td>
<td>0.71</td>
<td>3.23</td>
<td>2.26</td>
<td>373</td>
</tr>
<tr>
<td>PLC</td>
<td>19.23</td>
<td>4.4</td>
<td>2.64</td>
<td>61.45</td>
<td>2.41</td>
<td>0.20</td>
<td>0.68</td>
<td>3.4</td>
<td>5.25</td>
<td>453</td>
</tr>
<tr>
<td>Fly ash</td>
<td>36.53</td>
<td>19.39</td>
<td>5.27</td>
<td>18.62</td>
<td>4.92</td>
<td>5.69</td>
<td>0.85</td>
<td>2.06</td>
<td>0.30</td>
<td>—</td>
</tr>
<tr>
<td>Slag cement</td>
<td>35.75</td>
<td>9.72</td>
<td>0.50</td>
<td>35.66</td>
<td>13.05</td>
<td>0.33</td>
<td>0.52</td>
<td>2.93</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

### Table 2: Properties of concrete mixtures

<table>
<thead>
<tr>
<th>SCM replacement level, %</th>
<th>Cement type</th>
<th>w/cm</th>
<th>Slump, mm (in.)</th>
<th>Air content, %</th>
<th>Concrete temperature, °C (°F)</th>
<th>Density, kg/m³ (lb/ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>PC</td>
<td>0.45</td>
<td>100 (4)</td>
<td>6.8</td>
<td>18.8 (66)</td>
<td>2317 (145)</td>
</tr>
<tr>
<td></td>
<td>PLC</td>
<td>0.44</td>
<td>80 (3)</td>
<td>6.0</td>
<td>17.5 (64)</td>
<td>—</td>
</tr>
<tr>
<td>25</td>
<td>PC</td>
<td>0.44</td>
<td>75 (3)</td>
<td>6.2</td>
<td>18.1 (65)</td>
<td>2317 (145)</td>
</tr>
<tr>
<td></td>
<td>PLC</td>
<td>0.45</td>
<td>100 (4)</td>
<td>6.6</td>
<td>16.3 (61)</td>
<td>2328 (145)</td>
</tr>
<tr>
<td>40</td>
<td>PC</td>
<td>0.44</td>
<td>95 (3.75)</td>
<td>6.8</td>
<td>16.5 (62)</td>
<td>2303 (144)</td>
</tr>
<tr>
<td></td>
<td>PLC</td>
<td>0.44</td>
<td>80 (3)</td>
<td>6.0</td>
<td>15.5 (60)</td>
<td>2331 (146)</td>
</tr>
<tr>
<td>50</td>
<td>PC</td>
<td>0.44</td>
<td>95 (3.75)</td>
<td>6.5</td>
<td>14.5 (59)</td>
<td>2300 (144)</td>
</tr>
<tr>
<td></td>
<td>PLC</td>
<td>0.44</td>
<td>95 (3.75)</td>
<td>6.5</td>
<td>14.5 (58)</td>
<td>2309 (144)</td>
</tr>
</tbody>
</table>
temperature ranged from –2 to 5°C (28 to 41°F) and the relative humidity ranged from 44 to 93%. No problems were encountered with placing or finishing the slabs, and no differences were observed in the fresh properties of mixtures with PC or PLC at the same SCM replacement level.

**TESTING Methods**

During placing, a number of specimens were cast for laboratory tests, including:
- Compressive strength per ASTM C39;
- Rapid chloride penetration (electrical indication of ability to resist chloride ion penetration) per ASTM C1202;
- Resistance to rapid freezing and thawing per ASTM C666 Procedure A;
- Microscopical determination of air void system parameters per ASTM C457; and
- Scaling resistance to deicing chemicals per ASTM C672 and BNQ NQ 2621-900 Annex B.

Cores with a 100 mm (4 in.) diameter were also cut from the slabs at 35 days to determine the in-place strength per ASTM C42, resistance to chloride ion penetration per ASTM C1202, and apparent chloride diffusion coefficient per ASTM C1556.

**Results**

Compressive strength values for site-cast, laboratory-cured cylinders and cores are presented in Fig. 2. The highest strengths (for both PC and PLC mixtures) were recorded for mixtures with 40 and 50% SCM replacement levels. The cylinder results show a reduction in early-age strength with an increase in the level of SCM replacement, but this trend is reversed at later ages. At any particular age or SCM replacement level, the results show no significant or consistent difference between concrete produced with PC or PLC.

The results of the rapid chloride permeability tests conducted on cylinders at ages of 28 and 56 days and on cores cut from the slab at 35 days are shown in Fig. 3 and Table 3, respectively. While the results show that the charge passed in 6 hours decreases with increasing SCM content and with age, they also show no significant difference in performance between concretes produced with PC or PLC. All of the concretes containing SCMs meet the permeability require-
ments of CSA A23.1 for a C-1 exposure class (charge passed <1500 Coulombs at 56 days) and the mixtures with 40 and 50% SCM contents also meet the requirements for a C-XL class of exposure (charge passed <1000 Coulombs at 56 days).

Table 4 presents the results of hardened air void analyses and freeze-thaw tests. All mixtures had satisfactory air void parameters, reflected in the excellent durability factors (100 to 104%) after 300 cycles of freezing and thawing (ASTM C666 Procedure A).

The results from the two salt scaling test methods (the BNQ method and ASTM C672) are presented in Fig. 4. Specification limits vary for these tests. The Ontario Ministry of Transportation (MTO) imposes a maximum limit on the mass loss of 800 g/m² for concrete tested in accordance with ASTM C672 (MTO requires that a 3% NaCl solution be used in the test rather than the standard 4% CaCl₂ solution). The Quebec Ministry of Transportation considers concrete that scales less than 1000 g/m² in the BNQ test to have satisfactory performance. All of the concretes produced in this study met these performance requirements. There is a trend of increasing mass loss as the SCM content increases, however, and this is particularly marked in the concretes containing 50% SCMs. There is no consistent effect with regards to the use of PC or PLC.

Figure 5 provides the results from bulk-diffusion tests (ASTM C1556) conducted on cores taken at 35 days and immersed in a chloride solution for 42 days. The chloride profiles shown in Fig. 5 and the calculated diffusion coefficients presented in Table 5 show increasing resistance to chloride ion penetration with increasing SCM replacement levels up to 40%. There is an insignificant difference in performance between concretes with 40 and 50% SCM replacement levels, but we expect that the concrete with 50% SCM content will provide better resistance at later ages. The profiles and calculated coefficients indicate no consistent difference in performance between concretes produced with PC or PLC when comparing mixtures with the same SCM replacement levels.

The condition of the concrete pavements was examined visually on April 2, 2009, after a fairly harsh winter and numerous applications of deicing salts. Although there are instances of isolated damage at high points from a front end loader blade used for snow removal, the surfaces of all eight

### Table 3: Rapid chloride permeability test (ASTM C1012) results for cores taken from slabs at 35 days (values in Coulombs)

<table>
<thead>
<tr>
<th>Cement type</th>
<th>0</th>
<th>25</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>2400</td>
<td>1410</td>
<td>570</td>
<td>490</td>
</tr>
<tr>
<td>PLC</td>
<td>2350</td>
<td>1310</td>
<td>620</td>
<td>520</td>
</tr>
</tbody>
</table>

---

### PLC PER CSA A3001-08 AND A23.1-09

The Canadian Standards Association (CSA A3001-08) now permits the inclusion of up to 15% limestone in four types of portland limestone cement (PLC):

- Type GUL: General use cement;
- Type MHL: Moderate heat of hydration cement;
- Type LHL: Low heat of hydration cement; and
- Type HEL: High early-strength cement.

The performance requirements (setting time and strength) for these types of PLC are the same as those for the equivalent types of portland cement (PC) (Types GU, MH, LH, and HE), which are permitted to contain up to 5% limestone (realistically the maximum limestone content in portland cements is about 3.5% due to limits on the loss-on-ignition). With the exception of sulfate-exposure classes S-1, S-2, and S-3, CSA A23.1-09 permits the four types of PLC for use in all classes of concrete. The sulfate resistance of PLC concrete is currently under study.

Based on laboratory studies confirming that finer grinding is required to allow PLC mixtures to provide equivalent performance to PC mixtures,³ CSA PLCs are manufactured by intergrinding portland cement clinker with between 6 and 15% limestone. The clinker used to make PLC is the same clinker used to manufacture regular PC.
concretes are in excellent condition with no scaling evident (Fig. 6).

**PERFORMANCE**

The results of this study clearly show that incorporating SCMs in concrete can increase long-term strength and resistance to chloride ion penetration. These effects are relatively well established for concrete containing fly ash and slag cement, but in this case the benefits were apparent at relatively early ages and were even observed for 35-day-old concrete cores that were placed in cold-weather conditions. We believe these characteristics can be attributed to the composition of the blended SCM used in this study.

Although results are tempered somewhat by an apparent reduction in the resistance to salt scaling at higher replacement levels (50% SCM), it must be noted that accelerated laboratory salt scaling tests are very aggressive; thus, the poor test performance of concrete containing SCM does not accurately reflect field performance.\(^6,7\) Regardless of whether PC or PLC is used, however, it may be prudent to limit the SCM content in exterior flatwork that will be exposed to freezing and thawing in the presence of deicing salts.

While it must be noted that the PLC used in this study was ground to a significantly higher fineness than the PC, the data show that at a given level of SCM, there is no measurable, consistent difference between concretes produced with PC or PLC up to 50% SCM replacement levels. Of course, the level of SCM that can be used in other mixtures will depend on the properties of the SCM and the type of application.

These data indicate that the limestone content of cement can be increased from the level typically used in PC (about 3.5%) to 12% while maintaining equivalent performance. Such an increase in limestone content results in a reduction in the clinker content of the cement of more than 8%. When used with 40 to 50% SCM replacement levels, the effective reduction in clinker content in a mixture is in the range of 50%, with proportionate decreases in associated CO\(_2\) production.

**References**


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### TABLE 4:
**Air Void Parameters per ASTM C457 and Durability Factor (Resistance to Freezing and Thawing) per ASTM C666**

<table>
<thead>
<tr>
<th>SCM replacement level, %</th>
<th>Cement type</th>
<th>Air void parameters</th>
<th>Durability factor, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Air content, %</td>
<td>Spacing factor, μm</td>
</tr>
<tr>
<td>0</td>
<td>PC</td>
<td>5.3</td>
<td>173</td>
</tr>
<tr>
<td></td>
<td>PLC</td>
<td>5.6</td>
<td>187</td>
</tr>
<tr>
<td>25</td>
<td>PC</td>
<td>4.9</td>
<td>148</td>
</tr>
<tr>
<td></td>
<td>PLC</td>
<td>5.4</td>
<td>149</td>
</tr>
<tr>
<td>40</td>
<td>PC</td>
<td>5.6</td>
<td>164</td>
</tr>
<tr>
<td></td>
<td>PLC</td>
<td>5.3</td>
<td>165</td>
</tr>
<tr>
<td>50</td>
<td>PC</td>
<td>5.6</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>PLC</td>
<td>6.6</td>
<td>147</td>
</tr>
</tbody>
</table>

### TABLE 5:
**Calculated Values of Diffusion Coefficient $D_a \times 10^{-12} \text{m}^2/\text{s}$ from Bulk Diffusion Tests per ASTM C1556**

<table>
<thead>
<tr>
<th>Cement type</th>
<th>SCM replacement level, %</th>
<th>0</th>
<th>25</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>15.0</td>
<td>3.8</td>
<td>1.5</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>PLC</td>
<td>11.9</td>
<td>2.9</td>
<td>1.2</td>
<td>1.8</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4: Mass loss (salt scaling) results for tests conducted per: (a) BNQ NQ 2621-900 Annex B; and (b) ASTM C672

Fig. 5: Chloride profiles in concrete cores extracted from pavement slabs at 35 days and immersed in NaCl solution (165 g/l) for 42 days. Results for concrete with 40% SCM content have been omitted for clarity.
Received and reviewed under Institute publication policies.

Note: Additional information on the CEN, CSA, ASTM, AASHTO, and BNQ standards discussed in this article can be found at www.cen.eu, www.csa.ca, www.astm.org, www.transportation.org, and www.bnq.qc.ca, respectively.

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