Technical introduction to portland-limestone cement for municipal and provincial construction specifications

August 2023 | v2.0

Cement
Association
of Canada

Acknowledgments

The Cement Association of Canada would like to thank its members for their contributions to this resource, in addition to R. Douglas Hooton, Professor, University of Toronto and Michael D.A. Thomas, Professor, University of New Brunswick.

Cover Photography

Pan Am Soccer Stadium, Hamilton, ON
Architect: Cannon Design

Mattamy National Cycling Centre, Milton, ON
Architect: Cannon Design
Photographer: Harold Stiver

Telus Gardens, Vancouver, BC
Architect: Henriquez Partners Architects

Disclaimer

The technical resources provided in this document are for reference and educational purposes only, and are not intended to provide legal or other professional advice for any specific project or application. The examples used in this document should not be construed as engineering advice or guidance and project proponents must seek out and rely on duly qualified consultants and professionals for their projects. Companies and products which may appear in this document are provided with consent of those parties and this in no way constitutes and endorsement or representation or warranty of said companies and products. The Cement Association of Canada shall not be liable for any loss whether direct, indirect, incidental or consequential, arising from access to, use of or reliance upon any of the content of this document.

Contents

Introduction

With recent updates to the Canadian Standards Association (CSA) specifications relating to concrete and cementitious materials, the Canadian cement industry is fully poised to transition from the manufacturing of traditional portland cement (PC) to portland-limestone cement (PLC), including PLC-based blended hydraulic cement. In order to facilitate the transition towards PLC across Canada, the Cement Association of Canada has compiled this information package to assist agencies in their due diligence assessment for product adoption in local specifications.

Should additional information be required, or if your jurisdiction is interested in a webinar session with CAC staff, please contact us.

What is Portland-limestone Cement?

Portland-limestone cement is a more sustainable, lower carbon cement that reduces CO_2 emissions by up to 10% while still producing concrete of equivalent performance, including comparable strength and durability, to concrete produced with portland cement.

Portland-limestone cement's 10% reduction in CO_2 emissions occurs during the cement manufacturing process. While portland cement may contain up to 5% ground limestone, portland-limestone cement is made by intergrinding up to 15% limestone, reducing the amount of clinker required. By reducing the amount of clinker used in the manufacturing process, the associated energy demand and process emissions per tonne of PLC are reduced. As a result, the CO_2 emissions associated with PLC are less than those of traditional PC, while equivalent performance is maintained. Overall, the transition to PLC has the potential to save Canada approximately one megatonne of CO_2 emissions annually.

Why Portland-limestone Cement?

Concrete is the most widely used construction material on earth and increasing quantities are being produced to meet the needs of increased global population and urbanization. Portland cement, the main binder used in the production of concrete, is responsible for up to 90% of the embodied energy and carbon of concrete, and up to 8% of global anthropogenic CO_2 emissions. Over the last 30 years, the cement industry, especially in Canada, has invested in new production facilities that have substantially reduced its energy use and CO_2 emissions. In addition, the cement and concrete industry has widely adopted the use of supplementary cementing materials (SCMs) and chemical admixtures to improve performance and further reduce the cement clinker content of concrete, but global demand for concrete continues to increase.

In the last ten years, portland-limestone cements have been introduced and adopted in standards to meet the challenge of further reducing its CO_2 emissions by reducing the clinker content of cement without impacting on the performance of concrete.

How is Portland-limestone Cement Manufactured?

Portland-limestone cement's manufacturing process involves modifying the clinker, calcium sulphate and limestone proportions before the final grinding takes place. The limestone, being a softer material, is ground finer than the clinker. Along with selection of component proportions, this process of achieving the proper size and distribution of particles in PLC is commonly referred to as "optimizing" the cement.

The result of this optimization process is shown in Figures A and B below:

Figure A: Portland Cement

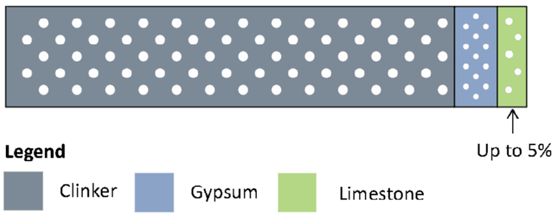
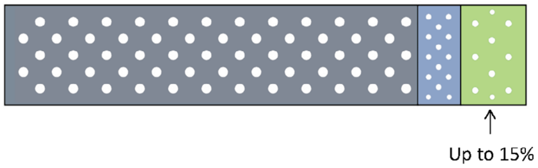


Figure B: Portland-limestone Cement



In addition, portland-limestone cement performs well when used together with supplementary cementitious materials (SCMs). Using portland-limestone cement together with SCMs provides further clinker reduction of the cementitious materials component of concrete, as shown later in Figure 9, and thus allows further reduction of Global Warming Potential (GWP).

History of Portland-limestone Cement Use

Portland-limestone cement has been used in Europe for over 35 years and has a long-established record of field performance in a variety of exposure conditions and applications. In Europe, portland cement is considered a premium product, as low-clinker cements (i.e. cements with a low clinker-to-cement ratio) are more prevalent than in North America. European cement standards allow up to 35% limestone content in PLC, which can restrict the use of such concrete mixes to select applications as limestone content increases. Canadian standards, meanwhile, have limited the inclusion of limestone in PLC to 15% in order to maintain equivalent performance when compared to traditional portland cement concretes.

Research on PLC with Canadian source materials began in 2006 before PLC was first introduced to the Canadian Standards Association cementitious materials standard in 2008 and concrete materials standard in 2009.

Canadian Specifications for PLC

The definition and specifications for PLC are contained in the CSA A3000 Cementitious Materials Compendium Standard. The specifications for using PLC in manufacturing concrete are contained in the CSA A23.1 Concrete Materials and Methods of Concrete Construction Standard.

CSA A3000 defines PLC and specifies its requirements in Clause 4.1, as highlighted in Table 1. “The proportion of limestone in portland-limestone cement shall be > 5% and ≤ 15% by mass”, and performance limits are the same as for traditional portland cement of the same type.

Table 1: CSA A3000 Cement Types

Name	Portland cement type	Portland-limestone cement type‡	Blended hydraulic cement type	
			Blended portland cement*	Blended portland-limestone cement†
General use cement	GU	GUL	GUb	GULb
Moderate sulphate-resistant cement	MS	MSL	MSb	MSLb
High early-strength cement	HE	HEL	HEb	HELb
High sulphate-resistant cement	HS	HSL	HSb	HSLb

** The suffix “b” indicates that the product is a blended portland cement.*
† The suffix “Lb” indicates that the product is a blended portland-limestone cement.
‡ The suffix “L” indicates that the product is portland-limestone cement.

Note: Moderate and low heat of hydration cement types were removed as part of the latest CSA A3000 amendment in May 2021.

Testing and Performance

Extensive research in Canada has demonstrated that PLC produces concrete with strength and durability properties equal to that produced using traditional portland cement. A series of relevant documents containing testing information and performance analysis can be found in the references section of this report. Of particular relevance are reports prepared for the Portland Cement Association (Tennis et al. 2011, Thomas and Hooton 2010 and 2016, and Hooton et al 2007), which identify the effects of PLC on both fresh and hardened concrete, as well as microstructure and chemical composition. As per concrete technology practice is advisable to assess the need of mix design adjustments to maintain performance properties when new. For ease of reference, selected properties have been highlighted below.

Workability

The workability of a PLC concrete mix is influenced most significantly by the fineness of the limestone. PLC is handled and can be used following the same workability approaches as conventional portland cement (i.e. use of superplasticizers and other additives will achieve the same desired results).

Setting Time

Cements with increased fineness and increased levels of fine limestone may have a slight accelerating effect on setting time (Hooton et al, 2007), but there have been no significant differences in time of set reported from field use to date.

Particle Size Distribution

In comparing PC to PLC at 15% limestone substitution, there is an increased level of microscopic particle packing allowing PLC to achieve equivalent performance in strength, resistance to freeze-thaw and de-icer salt scaling, chloride permeability and chloride diffusion, and alkali silica reactivity with a lower clinker factor and lower embodied energy and carbon.

Strength

Concrete strengths achieved by PLC concrete mixes containing up to 15% interground limestone are consistently comparable to that of PC concrete, both in terms of early strength development and ultimate compressive strength. As with all concrete properties, the type of cementitious material is not the sole variable affecting concrete strength, but PLC concretes provide similar strength performance as traditional PC concretes when equivalent materials are used, as shown in Figures 1 and 2 below.

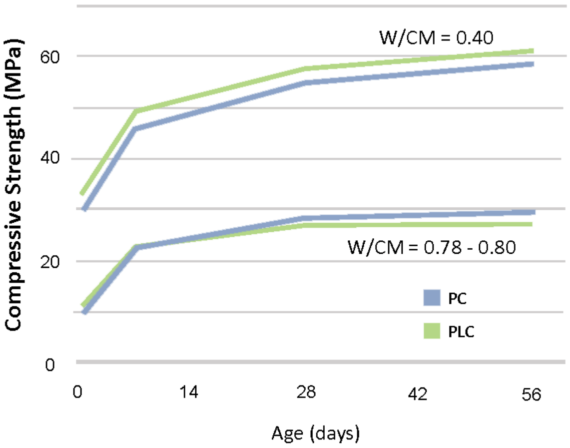


Figure 1: Strength development of PC and PLC without SCM at W/CM – 0.78 to 0.80 and 0.40 (Thomas and Hooton 2010)

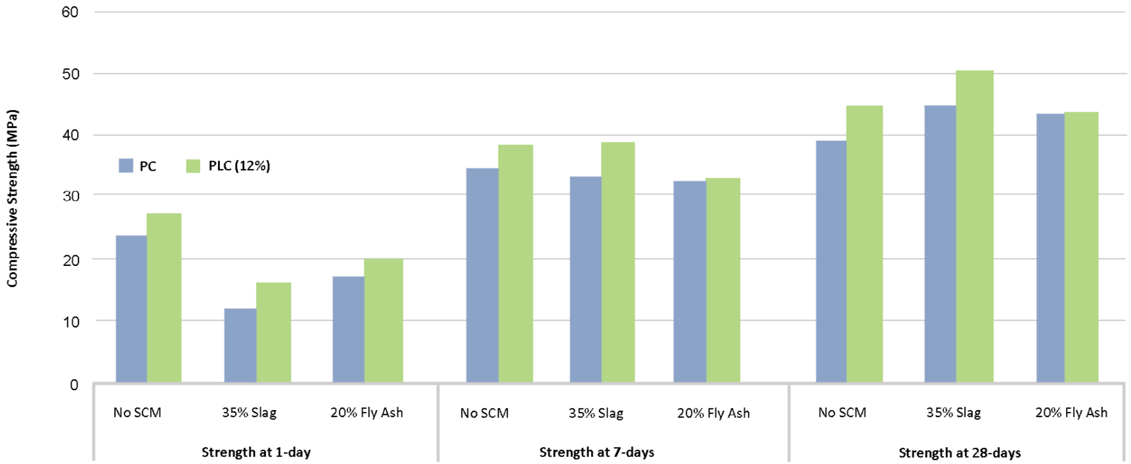
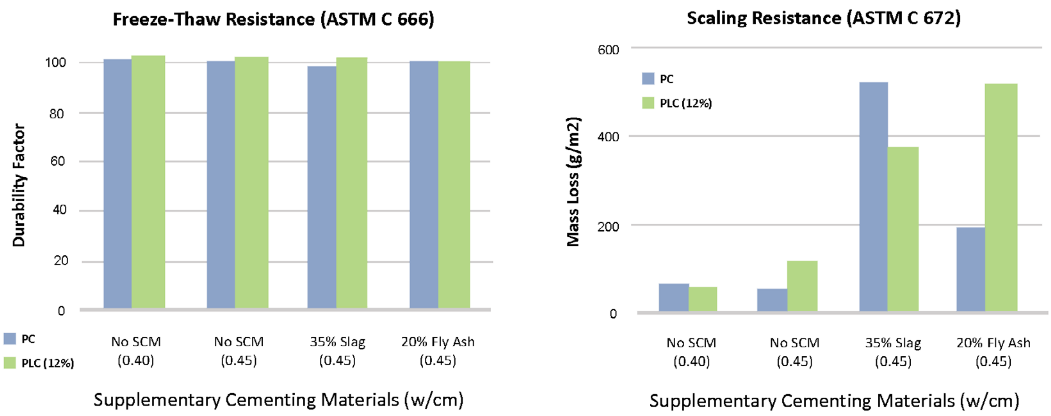


Figure 2: Strength development of PC and PLC mixes with and without SCM at W/CM = 0.45 (Thomas and Hooton 2010)

Freeze Thaw Durability and Scaling

The freeze-thaw and deicer-salt scaling data collected to date, as it pertains to PLC concretes, has shown no consistent difference between the behavior of equivalent PC mixes.



Note: While ASTM C 672 does not specify a limit for mass loss, some transportation agencies in North America have set maximum acceptable criteria, typically 1,000 g/m^2 or greater as determined by separate test protocols.

Figure 3: Results of freeze-thaw and de-icer salt scaling tests for PC and PLC concretes with and without SCM (Thomas and Hooton 2010)

Resistance to Chloride Penetration

Earlier studies indicated that PLC concrete provides similar resistance to the penetration of fluids as PC Concrete as illustrated in Figure 4:

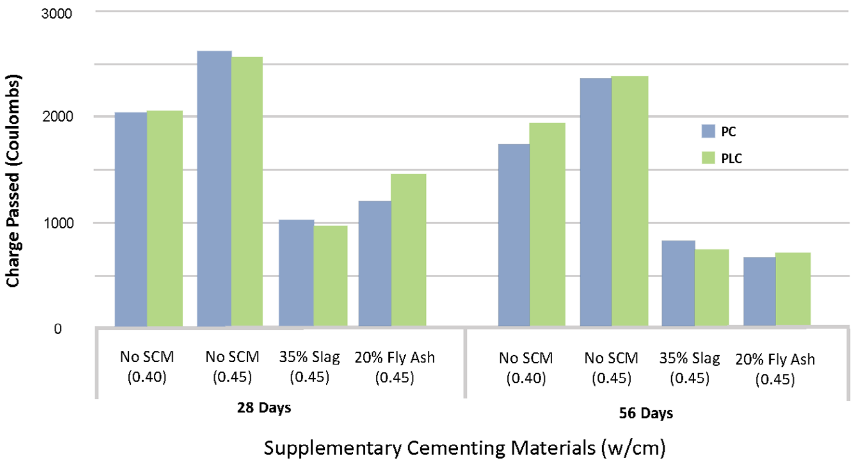
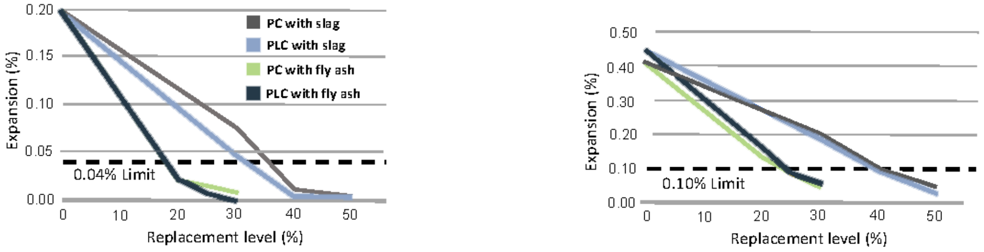


Figure 4: “Rapid Chloride Permeability Test” (ASTM C1202) data for PC and PLC concrete with and without SCM (Thomas and Hooton 2010)

A more recent 2021 study prepared for CALTRANS (see reference below) confirms the above results noting that based on the collected measurements during the analysis it can be concluded that the porosity, formation factor and chloride apparent diffusion of PLC based concrete mixes are comparable to those of ordinary portland cement (OPC) concrete mixes.

Mitigating Alkali Silica Reactivity

For alkali silica reactivity (ASR), tests have been performed on PC and PLC mortar bars and concrete prisms containing alkali silica reactive aggregates, as highlighted in Figure 5. Figure 6 highlights the expansion results from accelerated mortar bar test and concrete prism test from Study 4 using alkali-silica reactive siliceous limestone. The data has shown that there is no consistent difference between expansions produced with PC compared with PLC. There has also been no difference observed in the level of SCMs needed to mitigate ASR expansion.



a) Concrete prisms stored for 2 years over water at 38°C (100°F)

b) Mortar bars immersed for 14 days in an NaOH solution at 80°C (176°F)

Figure 5: Expansion results for concrete (ASTM C1293) and mortar (ASTM C1567) produced with alkali-silica reactive aggregate and blends of PC-SCM or PLC-SCM (Thomas et al 2013)

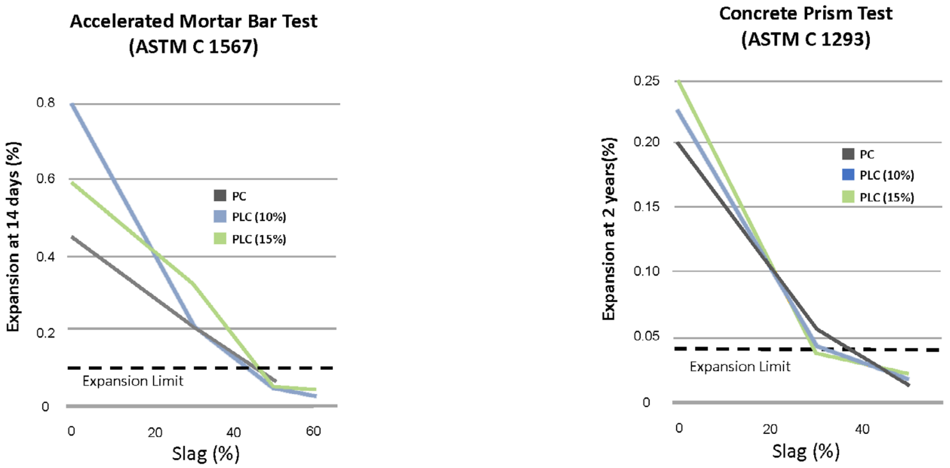


Figure 6: Expansion results from accelerated mortar bar test (left) and concrete prism test (right) from Study 4 using alkali-silica reactive siliceous limestone (Thomas et al 2010)

The 2021 CALTRANS study also shows that the PLC mixtures analyzed performed similar to or better than their like OPC mixtures when performing the ASTM C441, ASTM C1567 and AASHTO T 380 testing procedures.

Shrinkage

The drying shrinkage of concrete prisms produced with PC with and without SCMs is similar to concrete prisms produced with PLCs containing limestone contents of 10% and 15% with and without SCMs.

Table 2: CSA A23.1 (ASTM C157) Drying Shrinkage (2009 Field Data, w/cm = 0.40)

Length change (%)	GU 100%	PLC10 100%	PLC15 100%	GU 70% Slag 30%	PLC10 70% Slag 30%	PLC15 70% Slag 30%
28 days	0.036	0.037	0.037	0.026	0.027	0.025
1 year	0.069	0.061	0.062	0.058	0.052	0.053
2 years	0.067	0.068	0.065	0.062	0.06	0.067

The 2021 CALTRANS study also noted the following comments on shrinkage and creep:

1. The OPCs and their respective PLCs exhibited essentially the same shrinkage rate and total drying shrinkage for one year.
2. The tests concluded that both autogenous and unrestrained shrinkage in mortar samples were slightly less with increasing limestone content.
3. No statistically significant difference in cracking performance, consistent with the literature.

High Early Strength

As part of the cement and concrete industry's testing in the product development of PLC, a series of high early strength gain tests were performed, primarily to demonstrate performance in precast concrete applications where early stripping of formwork and handling of elements is common practice. As demonstrated in Figure 7, early strengths gains for PLC concretes are comparable to traditional mixes.

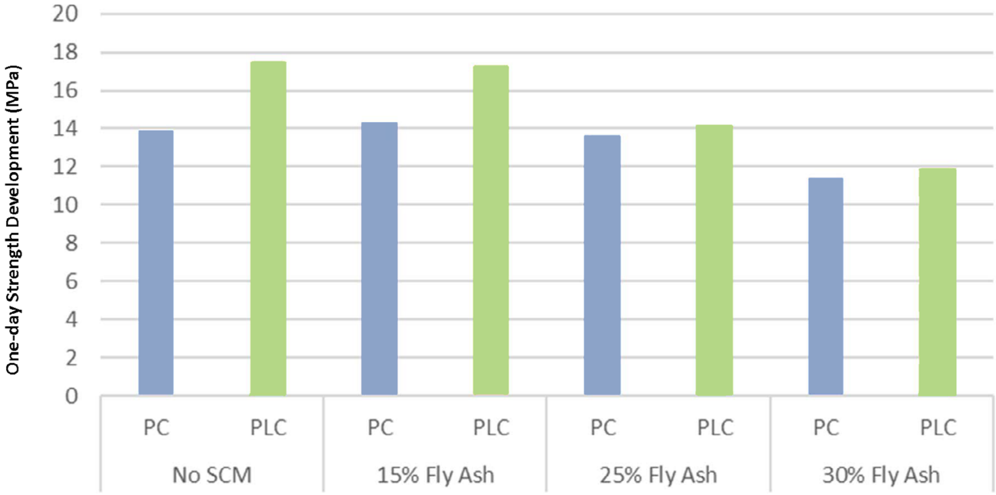


Figure 7: High early strength gain in PC and PLC concrete (Tennis et al. 2011)

Sulphate Exposure

In 2010 the Cement Association of Canada initiated, with the University of Toronto and the University of New Brunswick, a PLC sulphate resistance test program (Hooton and Thomas 2016). The program includes several different PLC and PC mix designs that include various levels of SCM replacements that are exposed in several different sulfate solutions and is ongoing. This program has produced consistent test results demonstrating the ability of PLC, when combined with supplementary cementing materials, to produce durable sulphate resistant concrete. This program contributed to the extensive testing and review of PLC before it was adopted by the CSA standards and approved for use in sulphate exposure environments.

It should be noted that the current Canadian PLC sulphate test program is the longest running program of its kind in the world. The test specimens continue to be monitored by the Canadian cement industry to evaluate and record their performance over time.

An update to the sulphate resistance test program (Hooton and Thomas 2016) was completed in 2018. An excerpt from this update for sodium and magnesium sulphate solutions is highlighted in Table 3 and 4 respectively.

Table 3: Visual Ratings of 0.40 w/cm concretes in outdoor exposure for up to 90 months exposure in Sodium Sulphate solution (Concentration 15,000 SO4 mg/L) (Hooton and Thomas 2016 - 2018 Update)

Exposure Period (months)	12	24	36	54	90
GU	Severe	Severe	Severe	Severe	Severe
GU 40% Slag	Undamaged	Minor	Minor	Minor	Moderate
PLC9	Severe	Severe	Severe	Severe	Severe
PLC9 40% Slag	Undamaged	Minor	Minor	Minor	Moderate
PLC15	Severe	Severe	Severe	Severe	Severe
PLC15 40% Slag	Undamaged	Undamaged	Undamaged	Minor	Moderate
HS1	Undamaged	Minor	Moderate	Severe	Severe

From the visual assessments of the field prisms highlighted in Table 3, after 90 months exposure, the performance of Type GU cement combined with 40% slag is similar to those of Type GUL PLC-9 and PLC-15 cements with 40% slag, showing moderate levels of surface damage

Exposure Period (months)	8	21	33	70
PLC10.5	Minor	Moderate	Severe	Severe
PLC10.5 25% Fly Ash	Undamaged	Undamaged	Undamaged	Minor
PLC10.5 35% Fly Ash	Undamaged	Undamaged	Undamaged	Undamaged
PLC10.5 40% Slag	Undamaged	Undamaged	Undamaged	Minor
PLC10.5 50% Slag	Undamaged	Undamaged	Undamaged	Undamaged
HS2	Undamaged	Undamaged	Minor	Minor-Moderate
HS3	Undamaged	Undamaged	Minor	Minor

After 70 months exposure, Type GUL cement, PLC-10.5 with 40% slag is performing the same as two Type HS portland cements (minor damage), and PLC-10.5 with 50% slag is performing better with no visual damage. The PLC-10.5 with 25% Class F fly ash is performing similarly to the two HS cements while the PLC-10.5 with 30% Class F fly ash is showing no evidence of damage.

Table 4: Visual Ratings of 0.40 w/cm concretes in outdoor exposure for up to 90 months exposure in Magnesium Sulphate solution (Concentration 15,000 SO4 mg/L) (Hooton and Thomas 2016 - 2018 Update)

Exposure Period (months)	12	24	36	54	90
GU	Severe	Severe	Severe	Severe	Severe
GU 40% Slag	Minor	Minor	Minor	Minor	Minor-Moderate
PLC9	Severe	Severe	Severe	Severe	Severe
PLC9 40% Slag	Minor	Minor	Minor	Minor	Minor-moderate
PLC15	Severe	Severe	Severe	Severe	Severe
PLC15 40% Slag	Minor	Minor	Minor	Minor	Minor-Moderate
HS1	Undamaged	Minor	Minor	Moderate	Severe

From the visual assessments of the field prisms given in Table 4, after 90 months exposure, the performance of Type GU cement combined with 40% slag is similar to those of Type GUL PLC-9 and PLC-15 cements with 40% slag, showing minor-moderate levels of surface damage. The Type HS cement concrete is showing a moderate level of damage.

Exposure Period (months)	8	21	33	70
PLC10.5	Minor	Moderate	Severe	Severe
PLC10.5 25% Fly Ash	Undamaged	Undamaged	Minor	Minor
PLC10.5 35% Fly Ash	Undamaged	Undamaged	Minor	Minor
PLC10.5 40% Slag	Undamaged	Undamaged	Minor	Minor
PLC10.5 50% Slag	Undamaged	Undamaged	Minor	Minor
HS2	Undamaged	Minor	Minor	Minor
HS3	Undamaged	Undamaged	Minor	Minor

After 70 months exposure, the PLC-10.5 mixtures with 40% slag, 50% slag, 25 and 30% Class F fly ash are performing the same as the two Type HS portland cements (minor damage).

The 2021 CALTRANS PLC study agreed with the Canadian findings that the PLC mixtures performed similar to, if not better than, their corresponding OPC mixtures in the presence of SCMs.

Fire Resistance

A 1984 study on Fire Resistance of Reinforced Concrete Columns conducted by T.T. Lie et al. of the National Research Council of Canada, Division of Building Research concluded that the largest influence on fire resistance of reinforced concrete columns is the aggregate size and type. For example, the study found the use of carbonate aggregate instead of siliceous aggregate will substantially increase the fire resistance of the columns. In addition, the National Building Code (NBC) equivalent thickness formula for concrete masonry walls only acknowledges the effect of aggregate on the fire resistance. All the historic data gathered by Portland Cement Association and National Research Council of Canada as identified in the reference, A Compilation of Fire Tests on Concrete Masonry Assemblies, to come up with the equivalent thickness formulas are based on aggregate types and fill in the cells, and does not get into the binder at all.

It is common knowledge that, the minimum concrete cover in structures is sufficient to create a barrier to the exposure of the concrete core in high temperatures, as a result concrete performance is not compromised, and this mechanism is not affected by the type of cement in the concrete mix.

Use in Canada

Since its introduction in Canadian project specifications, over 10,000,000 m^3 of PLC concrete has been placed. Through its inclusion in the CSA A3000 and CSA A23.1/A23.2 standards for cement and concrete, PLC is recognized within the National Building Code of Canada, and has been utilized in both private and public construction projects across Canada. A limited list of projects that have incorporated PLC in Canada is included in Appendix A. With respect to transportation agencies, a summary of the standing of PLC by province is highlighted in the figure below.

Figure 8: Map of acceptance by Provincial Transportation Agencies in Canada

Exclusions:

- **British Columbia does not allow PLC in structural precast concrete.**
- **Alberta does not allow PLC in structures or structural precast concrete.**
- **Saskatchewan does not allow PLC in structures or structural precast concrete.**
- **Manitoba does not allow PLC in structures or structural precast concrete.**
  - **MTI approves CSA A3001 products**
- **Quebec does not allow PLC in structures or structural precast concrete.**

In addition to broad adoption across provincial transportation agencies in Canada, PLC has been specified by many major municipalities across the country. Select municipalities with experience using and specifying PLC include Vancouver, Calgary, Edmonton, Saskatoon, Winnipeg, Toronto and most of the GTA, Windsor, Ottawa, and Montreal.

Use in Other Jurisdictions

Portland-limestone cement has an extensive proven track record in Europe in a variety of commercial and residential applications for over 35 years. The most popular cement sold in Europe today is PLC (CEM IIA-L) with a limestone content of up to 20%, though cement standards allow for PLC to be manufactured with up to 35% limestone content. It should be noted, however, that equivalent performance to regular portland cement is not the objective of the European cement standards, in contrast to Canada where equivalent performance has limited PLC to 15% limestone content.

In the United States, PLC was introduced into ASTM and AASHTO specifications in 2012. In addition, FAA P-501, AIA MasterSpec, UFGS 03 30 00 and ACI and ICC building codes permit use of PLC. The level of acceptance and inclusion by Departments of Transportation in the US is currently 46 with three additional states planning to accept. It is not known if individual State DOTs accept PLC usage for all applications including structures and precast. For more information on use of PLC based cements in the United States visit the following two PCA websites:

- https://www.cement.org/sustainability/portland-limestone-cement
- https://www.greenercement.com

Carbon Reduction Potential

As noted in the sections above, portland-limestone cement reduces CO^2 emissions compared to traditional cement, yet produces concrete of equivalent strength and durability. Once widely adopted across the country, PLC will reduce Canada's greenhouse gas emissions by up to 1 megatonne annually.

PLCs are also unique as they can be combined with other processes and technologies to further reduce the carbon intensity of concrete – for example, use of Type GUL to replace GU does not preclude the use of other carbon reducing strategies, such as:

1. the use of supplementary cementitious materials (SCMs) like fly ash and slag in blended cements and/or concrete;
2. reducing the paste volume fraction of concrete through use of optimized total aggregate gradations and chemical admixtures , or;
3. the use of newer processes involving the addition of carbon dioxide in concrete production (Carbon Capture and Utilization (CCU) technologies are becoming a key technology in concrete's low-carbon transition).

An example of the clinker reduction potential of PLC using SCMs at various substitution rates is highlighted in Figure 10.

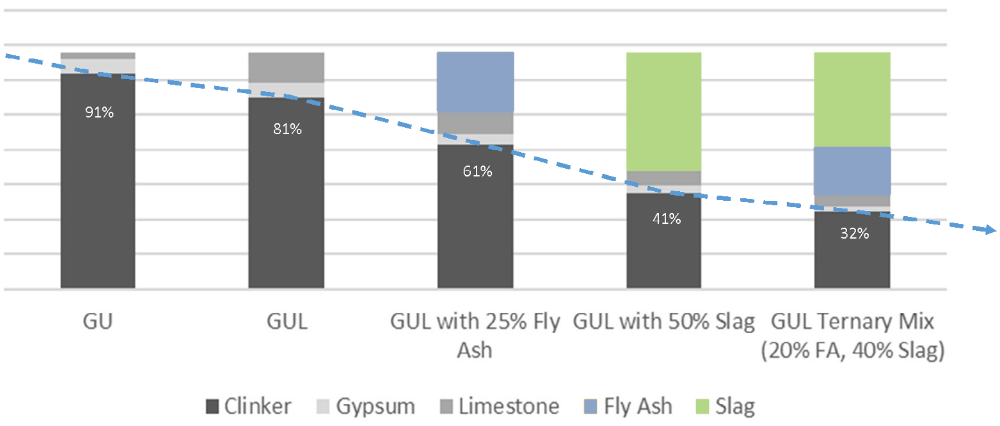


Figure 10: Clinker reduction potential of portland Cement and PLC with and without SCMs (example for 340 kg cementitious content concrete mixture)

Summary

Introduced to Canadian standards in 2009, PLC concrete is now being commonly used in many jurisdictions in Canada as a sustainable direct replacement to PC concrete with equivalent performance. It can be poured, pumped or placed using conventional means and finishes as well or better than PC based concrete with no known drawbacks.

As of 2020, all members of the Cement Association of Canada produce PLC, including facilities in British Columbia, Alberta, Ontario, Quebec, and Atlantic Canada. Local expertise is available to assist designers and regulators in the specification, implementation, and review of PLC concretes, as outlined in the following section.

Key Contacts

For more information on portland-limestone cement, please contact the following individuals:

Cement Association of Canada
Stamatima Chasioti, Director, Codes and Standards / Engineer
schasioti@cement.ca

Ash Grove, a CRH Company
Richard Sluce, Director of Technical Services, North Region
richard.sluce@ashgrove.com

Heidelberg Materials
Ana Milena Rebellon, Technical Services Engineer
ana.rebellon@heidelbergmaterials.com

Lafarge Canada
Matt Dalkie, P.Eng, LEED AP BD+C, Technical Services Engineer
matt.dalkie@lafargeholcim.com

St. Marys Cement Group
Nick Popoff, Vice President of Product Performance and Technical Services
nick.popoff@vcimentos.com

Professor Doug Hooton, University of Toronto (d.hooton@utoronto.ca)

References

Bharadwaj, Keshav, et all, *CALTRANS: Impact of the Use of Portland-Limestone Cement on Concrete Performance as Plain or Reinforced Material*, April 30, 2021 revised June 29, 2021, 320 pages

Hooton, R. D.; Nokken, M. R.; and Thomas, M. D. A., *Portland-Limestone Cement: State-of-the-Art Report and Gap Analysis for CSA A3000*, Portland Cement Association, SN3053, 2007, 59 pages. Available at: http://www2.cement.org/pdf_files/sn3053.pdf

Portland Cement Association. (2021). Status of acceptance of portland-limestone cement in state DOT specifications

Tennis, P. D.; Thomas, M. D. A.; and Weiss, W. J., *State-of-the-Art Report on Use of Limestone in Cements at Levels of up to 15%*, Portland Cement Association, SN3148 by, 2011, 78 pages

Thomas, M.D.A. and Hooton, R. D., T*he Durability of Concrete Produced with Portland-Limestone Cement: Canadian Studies*, Portland Cement Association, SN3142, 2010, 28 pages

Thomas, Michael D.A; Delagrave, Anik; Blair, Bruce; and Barcelo, Laurent, *Equivalent Durability Performance of Portland Limestone Cement*, Concrete International, December 2013, 7 pages

Yasien, Ahmed, Ghazy, Ahmed and Bassuoni, Mohamed, *Performance of Concrete Pavement Incorporating Portland Limestone Cement in Cold Weather*, MDPI, Sustainability 2022,14,183, 2022, 12 pages

Additional References

A more fulsome collection of technical reports, white papers and studies on the use of Portland-limestone cement can be found in the Dropbox link provided. The information is organized according to the folder contents as described in the list below.

PLC Reference File Folder

Environmental Benefits

a. Cement Association of Canada, “Environmental Product Declaration (EPD) for General Use (GU) and Portland-limestone (GUL) Cements”, CSA Group, March 31, 2016

b. An Environmental Life Cycle Assessment of Portland- limestone and Ordinary Portland Cements in Concrete, Lindita Bushi and Jamie Meil, Athena Sustainable Materials Institute, January 2014

Performance Testing and Analysis

a. Performance of Portland Limestone Cement Concrete Pavements Canadian field trials show equivalence, Ashlee Hossack, Michael D.A. Thomas, Laurent Barcelo, Bruce Blair, and Anik Delagrave, Concrete International, January 2014

b. Portland-Limestone Cement: State-of-the-Art Report and Gap Analysis for CSA A 3000, R. D. Hooton, M. Nokken, and M. D. A. Thomas, University of Toronto, 2007

c. Aqel, M. A., Steam Cured Self-Consolidating Concrete and the Effects of Limestone Filler, Mohammad A. Aqel, University of Toronto Thesis, 2016

d. Sulfate Resistance of Concretes Containing Portland-Limestone Cement, Presentation by Doug Hooton and Michael Thomas, March 2013, Alberta ACI

e. Evaluation of the effect of tricalcium aluminate content on the severity of sulfate attack in Portland cement and Portland limestone cement mortars, Ashlee M. Hossack, Michael D.A. Thomas, Cement & Concrete Composites, Accepted 22 October 2014, Available online 15 November 2014

f. The effect of temperature on the rate of sulfate attack of Portland cement blended mortars in Na2SO4 solution, Ashlee M. Hossack, Michael D.A. Thomas, Cement and Concrete Research, Accepted 24 February 2015

g. Varying fly ash and slag contents in Portland limestone cement mortars exposed to external sulfates, Ashlee M. Hossack, Michael D.A. Thomas, Construction and Building Materials, Accepted 4 January 2015

h. Field performance of Portland limestone cement concretes exposed to cold-temperature sulfate solutions, A. Hossack, M.D.A. Thomas, E. Moffatt, Workshop on External Sulfate Attack. Field Aspects and Lab Tests, 24-25 May 2018

i. Performance and Sustainability Application of Portland-limestone cements in concrete paving, Brooke W. Smartz, Todd S. Laker, and Thomas Van Dam, Concrete International September 2013

j. Sulfate Resistance of Mortar and Concrete Produced with Portland-Limestone Cement and Supplementary Cementing Materials, R. D. Hooton and M. D. A. Thomas, Portland Cement Association, 2016 Report SN3285

k. Sulfate Resistance of Mortar and Concrete Produced with Portland-Limestone Cement and Supplementary Cementing Materials: Recommendation for ASTM C595/AASHTO M 240, R. D. Hooton and M. D. A. Thomas, Portland Cement Association 2016 Report SN3285A

l. Sulfate Resistance of Mortar and Concrete Produced with Portland-Limestone Cement and Supplementary Cementing Materials: Recommendation for CSA A3000, R. D. Hooton and M. D. A. Thomas, Portland Cement Association, 2016 Report SN3285b

Performance Testing and Analysis

m. State-of-the-Art Report on Use of Limestone in Cements at Levels of up to 15%, P. D. Tennis, M. D. A. Thomas, and W. J. Weiss, Portland Cement Association, 2011

n. Field Trials of Concretes Produced with Portland Limestone Cement New CSA cement type performs well in an aggressive environment, Michael D.A. Thomas, Doug Hooton, Kevin Cail, Brenton A. Smith, John de Wal, and Kenneth G. Kazanis, Concrete International, January 2010

Fire Resistance

a. T.T. Lie et all, Fire Resistance of Reinforced Concrete Columns, National Research Council Canada, Division of Building Research, DBR Paper No. 1167, NRCC 23065, February 1984

b. Robert Day, The Potential for the Use of Limestone Cement, Limestone Powder and Supplementary Cementing Materials in Mortar, Grout and Block for Masonry Construction in Canada, Department of Civil Engineering, University of Calgary, February 2010

c. SBCCI Public Safety Testing and Evaluation Services, inc., A Compilation of Fire Tests on Concrete Masonry Assemblies, Volume 1 of 5, Summary of Test Data, June 1993

US Field Studies

a. US PLC Project List by Location

b. Portland-Limestone Cement after 10 Years in the Field, Al Innis, Todd Laker, Brooke Smartz, Adam Fox, Edited by Sabrina Shields-Cook, CP Road Map, October 2018

c. Performance and Sustainability, Application of portland-limestone cements in concrete paving, Brooke W. Smartz, Todd S. Laker, and Thomas Van Dam, Concrete International, September 2013

d. Use of Performance Specified Cements in Colorado Transportation Projects: Case Studies, Thomas J. Van Dam, Brooke W. Smartz, TRB 2010 Annual Meeting, November 13, 2009

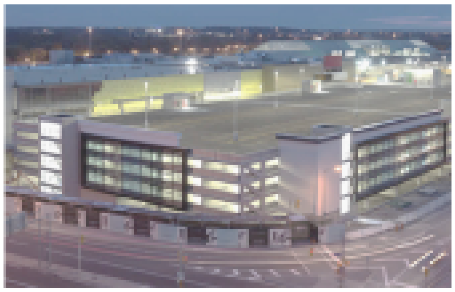
e. Performance Enhancing Research shows ways of reducing concrete's carbon footprint, Thomas J. Van Dam, Brooke W. Smartz, and Todd S. Laker, Roads and Bridges Magazine, November 2010

f. Use of Performance Cements (ASTM C1157) in Colorado and Utah: Laboratory Durability Testing and Case Studies, Thomas J. Van Dam, Brooke W. Smartz, and Todd S. Laker, date and publication unknown

Other Field Studies

a. Relationships of Cement Paste Mineralogy to Porosity and Mechanical Properties, T. Matschei, D. Herfort , B. Lothenbach, F. P. Glasser, Modelling of Heterogeneous Materials, Edited by M. Jirasek, Z. Bittnar and H. Mang, Prague, 2007

Appendix A: Project Examples



Bayshore Shopping Centre, Redeveloped Parking Garage
Ottawa, ON

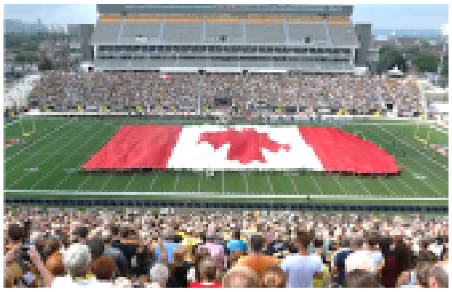
64,000 m³ (2011 – 2016)

- GUL with 40% to 60% Slag and 40mm Limestone
- Low Heat requirement, <0.04% Linear Shrinkage, Salt Scaling requirements, RCP <1000
- 3-feet thick raft slabs, 4 parkades with 35 MPa-C1 up to 55 MPa concrete

YMCA: Building & Retaining Wall
Brantford, ON

~ 7,500 m³ (2016 – 2017)

- 75-80% T-GUL with 20-25% Slag and 20mm Limestone
- 25-N, 32-C2, 35-N/F2, and 50-F2 mixes
- Footings, slabs, walls, columns, retaining wall, high-early crane pads



Pan AM Soccer Stadium
Hamilton, ON

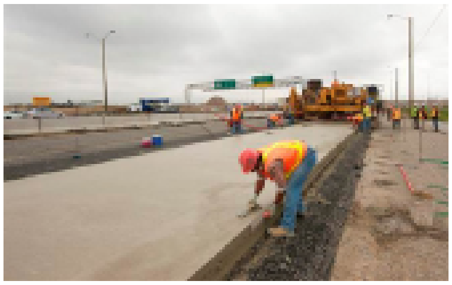
~ 11,000 m³ (2013 – 2014)

- Strengths ranging from 10 MPa for mud matt to 35 MPa-C1 structural walls
- Specialty mixes including SCC, Early Strength, and Cold Weather Setting
- LEED Silver

Milton Velodrome
Milton, ON

13,250 m³ (2013 – 2014)

- Strengths ranging from 10 MPa for mud matt to 40-C1 structural walls and slab
- Specialty mixes including Early Strength, and Cold Weather Setting
- LEED Silver



Hwy 401 & Hurontario Off-ramp
Mississauga, ON

~ 450 m³ (2010)

- 75% Type GUL and 25% Slag cement
- 30 MPa w/air concrete, tested for AVS, RCP, Salt Scaling, and Drying Shrinkage
- MTO Contract with 500 linear meter section, one lane wide

Repair of Hwy 6 & 403 Overpass
Hamilton, ON

~ 60 m³ (2017)

- 75% PLC and 25% Slag cement
- 30 MPa w/air concrete patch work mix design, meeting AVS and RCP (<2500C)
- MTO night work project
- Project example highlights compatibility of PLC with existing Portland Cement infrastructure

The Mark

Vancouver, BC

(2014)

- First building started with PLC in Vancouver area
- 47 storeys residential
- LEED Gold

Brock Commons

Vancouver, BC

~ 37,123 m³ (2017)

- 18-storey hybrid building
- 2 x concrete elevator and staircase cores
- concrete topping on all floors
- UBC student residence building
- LEED Gold

Saint John Field House

Saint John, NB

2,700 m³ (2018 – 2019)

- 127 000 ft² Complex features two indoor turf fields, 200 meter indoor track, fitness center, child care and newcomer connection services

Highway 40

L'Assomption, QC

338 m³ (2010)

- 100% Type GUL
- 35 MPa w/air concrete, tested for AVS, RCP, Salt Scaling, and Drying Shrinkage
- MTQ Contract with 250 linear meter section, one wide lane

Sidewalks for City of Montreal

Montreal, QC

±10 000m³/year (2017 - 2020)

- 80% PLC with 20% of GUb-8SF
- 32 MPa w/air 0.45 W/C
- A23.2-22C Scaling resistance (<500g/m² mass loss)

Huron Church Road

Windsor, ON

1,050 m³ (2020)

- Cement treated Open Graded Drainage Layer (OGDL) with PLC

Pay Center (Federal Government)

Miramichi, NB

5,500 m³ (2015- 2016)

- 107 000 ft² office space
- LEED Gold
- 25-N, 30-N, 30-F1, 32- C2, 35-N, 35 C1, 40-N

Cyberpark

Fredericton, NB

3,300 m³ (2018-2019)

- 150,000 ft² building, housing cybersecurity for Canada's infrastructure including defence systems, finance, transportation, hydro-electric production and water.
- 25-F2, 30 N-CF 35 N-CF, 32-C2 25 N Blockfill wall infill

Metro Distribution Facility

Toronto, ON

2,000 m³ (2020)

- Roller Compacted Concrete (RCC) truck yard with PLC

Charlie West Condo

Kitchener, ON

27,000 m³ (2018-2020)

- 2,700 m³ in raft slab foundations
- Concrete up to 65 MPa in Strength

One Wellington Condominium

Brantford, ON

7,500 m³ (2018-2020)

- Waterproof Concrete, Tempo High Early Concrete helped keep the customers schedule
- 1,200 m³ raft slab

Google Building

Kitchener, ON

17,000 m³ (2019-2021)

- 6,000 m³ of raft slabs
- Included low heat concrete mixes

Library and Archives Preservation Facility
Ottawa, ON

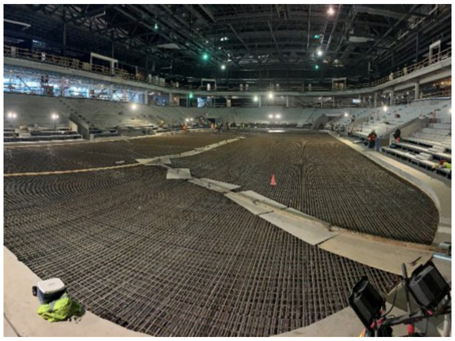
22,000 m³ (2020- 2021)

- GUL with up to 40% Slag
- CSA Class C-1, including Salt Scaling requirements, RCP <1500
- 3' thick Type LH raft slabs and interior wall sections of 30' in height.

Mattawa Plains Compound
CFB Petawawa, ON

30,000 m³ (2018-2020)

- 100% GUL with 20-30% Slag and 20mm Limestone.
- 25-N, 30-N/F-1, 32-C2, 35-N/C-1.
- 10 Structures on 80 acres including Parking structures with both High-early strength and Corrosion Inhibitor



Centre Slush Puppie Four Ice Center
Gatineau, QC

10,000 m³ (2019-2021)

- 100% GUL with 20%-30% Slag
- CSA Class C-XL 50 MPa with Granite for the Zamboni slabs to all 4 ice pads
- CSA Class C-1 35 MPa with 30% Slag, Corrosion Inhibitor and HR Superplasticizer for the parking garage portion

National Holocaust Monument
Ottawa, ON

3,350 m³ (2018-2020)

- Architectural mixes with Type GUL with up to 20%-60% Slag
- CSA Class C-1 35 MPa SCC mix with 50% Slag
- CSA Class C-1 35 Mpa with 30% Slag, Corrosion Inhibitor and HR Superplasicizer
- Received the Ontario Concrete Award for Architectural Hardscape

Box Culvert Structure for a Subdivision
Ottawa, ON

(2022)

- GUL cement
- 1200mm span by 900mm rise with a run length of 32.5m
- Precast producer –M CON Products

Light Weight Fill
St. Agatha, ON

300 m³ (2021)

- 80% Type GUL with 20% Slag
- 100 tonnes of GUL
- Cematrix lightweight cullular concrete

Trump International Hotel and Tower
Vancouver, BC

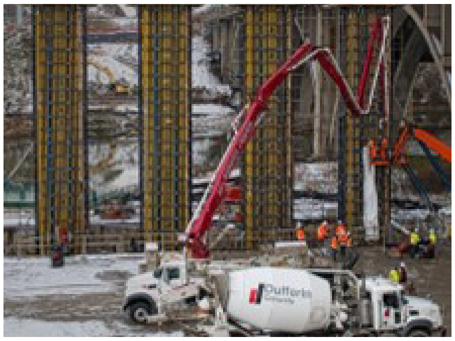
~35,127 m³ (2016)

- 63 storeys
- Hotel and residential
- LEED Silver

Paradigm Condominiums Burlington
Burlington, ON

~40,000 m³ (2015-2018)

- Three buildings
- 100% Type GUL
- Up to 80 MPa compressive strength
- Paradigm's highly-reflective "white" roof reduces cooling requirements during the summer months, and lessens the heat island effect



Queen Elizabeth Highway Bridge Piers
Mississauga, ON

~600 m³ (2011-2022)

- 100% Type GUL
- 25% slag cement
- 8 piers constructed by Ellis Don

River & Fifth Condo
Toronto, ON

7,000 m³ (2020-2023)

- 100% Type GUL
- 37 storey conde
- Congested city traffic and small footprint for concrete delivery

Hutton Transport Truck Maintenance Shop
Bowmanville, ON

500 m³ (2014)

- GUL with 25% Slag
- 15NA & 25NA Footings, 35A exterior slab, 35NA interior floor

Concrete Pipe for Southdale Road
London, ON

(2022)

- GUL with 25% Slag or 35% newcem plus
- Forterra pipe was the manufacurer

Additional Projects

Concrete Pavement Test Sites (2007)

- Gatineau Ready Mix Concrete Plant, Gatineau, QC
- Exshaw Cement Plant, Exshaw, AB
- Brookfield Cement Plant, Brookfield, NS

Ontario

- Reliance Construction Condos, Oakville (2019-2021)
- Trafalgar Heights, Oakville (2018-2021)
- Buttcon Limited, Hyatt Hotel, Niagara Falls (2020-2022)
- Berkeley Parliament Developments Condo Tower, Toronto (2016-2019)
- Bel East Corporation 25-storey Condo, Toronto (2017-2020)
- Lash Distinction 14-storey Condo, Toronto (2017-2020)
- Mattamy Homes, Trafalgar Rd and Highway 5, Oakville
- Blair Station, Ottawa Light Rail Transit Confederation Line, Ottawa
- SOHO Italia Condominiums, 2020-2021, Ottawa (15,000 m^3)
- Parkdale Condominiums, Ottawa (16,000 m^3)
- Petrie's Landing Condominiums, Ottawa (12,000 m^3)
- Le Colombia Condominiums, Ottawa, (8,000 m^3)
- Baseline Condominiums, Ottawa (14,000 m^3)
- Metal Works Phase 3 Condo, Guelph (9 000 m^3)
- Jackson Condos, Hamilton (7,000 m^3)
- Gallery Condos, Burlington (20,000 m^3)
- Casa Di Torre Condo, Hamilton (7,000 m^3)
- Multiple Industrial Buildings, Guelph and Brantford (20,000 m^3)
- Gaslight District Condos Cambridge

Ontario Ministry of Transportation (limited basis)

- Barrier Wall, QEW – Burloak Drive to Brant Street (Nov 2009)
- Concrete Pavement, Highway 401 to Hurontario Street (Sep 2010)
- Slipform Barrier, Hwy 2 (west), east of Front Street, Sarnia (Oct 2011)
- Sidewalk, Airport Road near Collingwood (Jun 2012)
- Precast Median Barrier, Hwy 401 near Trenton, Glen Miller Road to Hillaire Road (Nov 2012)
- Sidewalk, Laird Overpass, Guelph (Oct 2013)

British Columbia

- Telus Gardens, West Georgia and Seymour, Vancouver
- Solo District, Willingdon and Lougheed, Burnaby
- Vancouver House, Pacific and Howe, Vancouver
- Teck Acute Care Centre, BC Children's Hospital, Vancouver
- Wall Centre False Creek
- Anthem Station Square, Burnaby
- Axiom Cadero 26-storey residential building, Vancouver
- Arbutus Shopping Centre, Vancouver
- Evelyn residences by OMNI, West Vancouver
- HWY 1 248st overpass
- HWY 1 Mountain Highway Interchange
- Ongoing work on interchange updates on HWY 1 in Vancouver
- Annacis Island Wastewater Treatment Plant
- North Shore Wastewater Treatment Plant
- Iona Wastewater Treatment Plant upgrade
- All City of Vancouver works
- YVR projects have been supplied PLC for the last two years

Atlantic Canada

- Dr. Georges-L.-Dumont Surgical Suite Addition, 2018-2019, Moncton, New Brunswick (3,400 m^3)
- Horizon Place Apartments, 2016-2017, Moncton, NB (15,600 m^3)
- Hyatt, 2018-2019, Moncton NB (5,200 m^3)
- Emma Place, Moncton, New Brunswick
- iHop, Moncton, New Brunswick
- Day and Ross, Moncton, New Brunswick
- East Hants Pool, 2018-2020, Truro, Nova Scotia (1,600 m^3)
- Hilton, Fredericton, New Brunswick
- Sobeys, Fredericton, New Brunswick
- Shannex, Fredericton, New Brunswick
- 81 Regent Street, Fredericton, New Brunswick
- Integrated Health Services CFB Gagetown, Fredericton, New Brunswick
- Waverly Mixed-Use Office Building, 2019-2020, Fredericton, New Brunswick (3,400 m^3)
- Marshalls, Fredericton, New Brunswick
- 2 Shannex, Miramichi, New Brunswick
- Centennial Bridge, Miramichi, New Brunswick
- Saint John, New Brunswick

Atlantic Canada (continued)

- Brunswick Square, Saint John, New Brunswick
- Giant Tiger, Saint John, New Brunswick
- Petrocan/A&W, Saint John, New Brunswick
- Saint John Laundry Building, Saint John, New Brunswick
- Shepody Bridge, Sussex, New Brunswick
- Compound Maintenance Facility Fundy Park, Sussex, New Brunswick
- Wharf Repairs at Metaghan, Yarmouth, Nova Scotia
- Wharf Repairs at Wedgport, Yarmouth, Nova Scotia
- TRU Hotel by Hilton, 2019-2020, Yarmouth, Nova Scotia (650 m^3)
- Net Zero Energy Building, Yarmouth, Nova Scotia
- Par en Bas School, 2020, Yarmouth, Nova Scotia (1,150 m^3)

Quebec

- Approved for all City of Montreal buildings
- Approved for MTQ concrete paving
- Sobeys warehouse Pointe-Claire (2020)
- 50 Storey condos ''Tour des Canadiens'', Montreal
- REM project (2020-2023)
- Centre Hospitalier Universitaire Sainte-Justine, Montreal

Appendix B: Case Study – City of Winnipeg GUL and GU Concrete Pavement Test Sections

The City of Winnipeg and the University of Manitoba conducted research on the use of Portland limestone cement (PLC), comprising up to 15% limestone filler, in transportation infrastructure projects such as concrete pavements. The research notes that laboratory tests have substantiated the equivalent or superior resistance of concrete made with PLC relative to concrete made with general use (GU) cement to durability exposures including acids, sulfate salts and chloride-based deicing salts. The research reviews the performance of two sections of concrete pavement, one with GUL cement and the other GU cement, constructed in Winnipeg Manitoba. Data collected included fresh properties, strength, absorption and chloride ions penetrability, as well as microstructural features. The field trials showed that the GUL concrete sections had equivalent or superior performance compared to the GU cement-based section in terms of fresh, hardened and durability properties.

The following excerpts from the research paper entitled, Performance of Concrete Pavement Incorporating Portland Limestone Cement in Cold Weather, show how the GUL test section has performed as well as or better than the GU test section:

Table 4 below shows the compressive strength was higher for the GUL based concrete pavement test section than the adjacent GU test section. In addition, the coulombs rating was better for the GUL section as it had a very low rating compared to a low rating for the GU section.

Figure 3 below shows pictures of the GUL and GU sections of concrete pavement placed three years ago. Both pavements, when placed with a slipform paver showed virtually no scaling. Only the PLC concrete pavement placed by hand showed any signs of scaling and it was minimal.

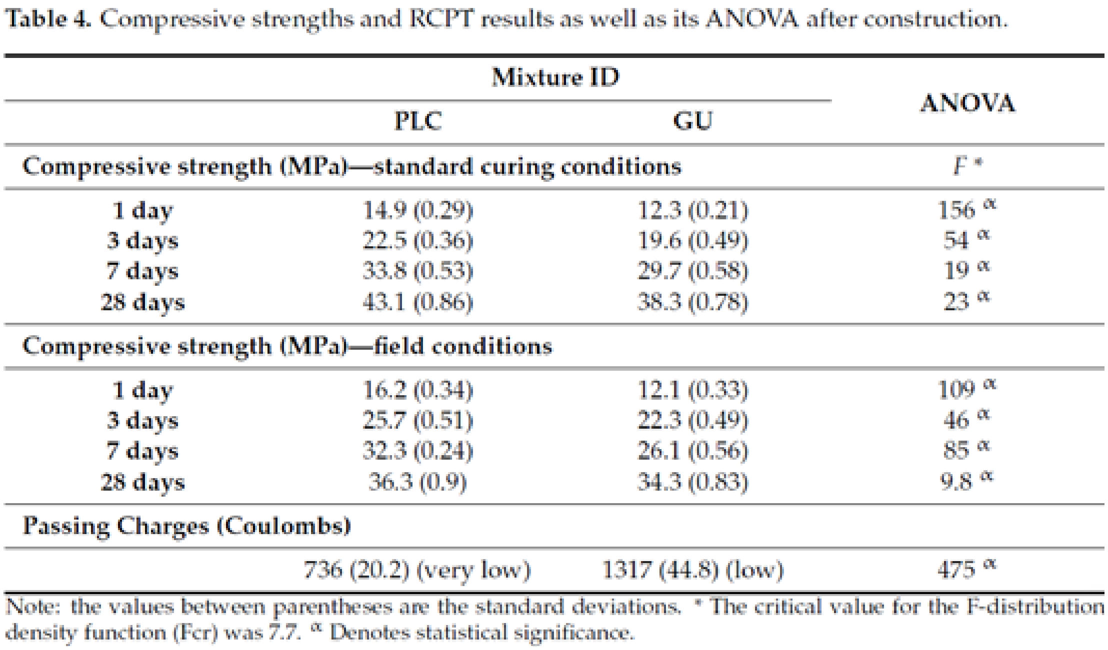


Table 4. Compressive strengths and RCPT results as well as its ANOVA after construction.

	Mixture ID		ANOVA
	PLC	GU	
Compressive strength (MPa)—standard curing conditions			F^*
1 day	14.9 (0.29)	12.3 (0.21)	156 $^{\alpha}$
3 days	22.5 (0.36)	19.6 (0.49)	54 $^{\alpha}$
7 days	33.8 (0.53)	29.7 (0.58)	19 $^{\alpha}$
28 days	43.1 (0.86)	38.3 (0.78)	23 $^{\alpha}$
Compressive strength (MPa)—field conditions			
1 day	16.2 (0.34)	12.1 (0.33)	109 $^{\alpha}$
3 days	25.7 (0.51)	22.3 (0.49)	46 $^{\alpha}$
7 days	32.3 (0.24)	26.1 (0.56)	85 $^{\alpha}$
28 days	36.3 (0.9)	34.3 (0.83)	9.8 $^{\alpha}$
Passing Charges (Coulombs)			
	736 (20.2) (very low)	1317 (44.8) (low)	475 $^{\alpha}$

Note: the values between parentheses are the standard deviations. * The critical value for the F-distribution density function (Fcr) was 7.7. $^{\alpha}$ Denotes statistical significance.

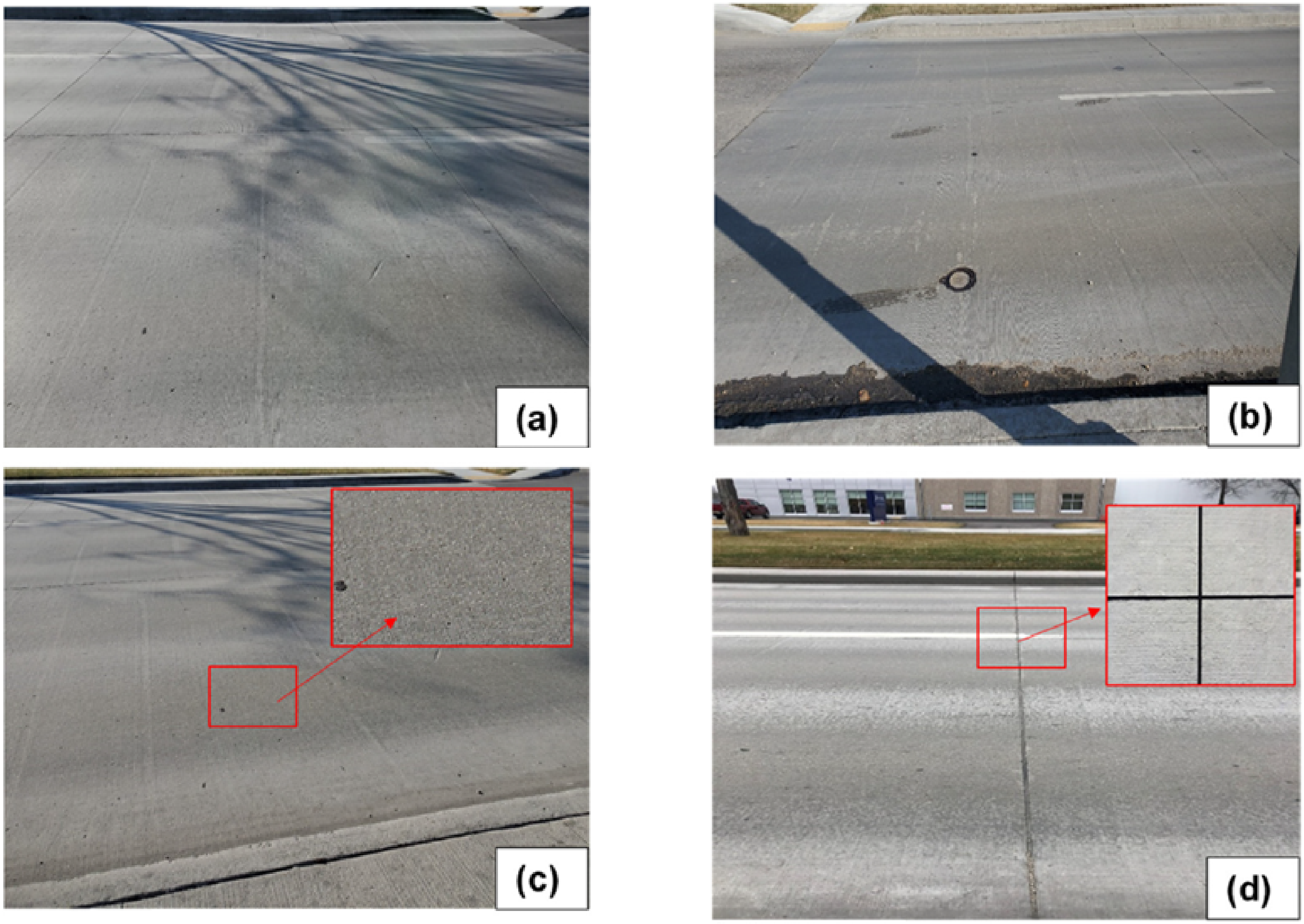


Figure 3. Visual features of the pavement sections after three years: (a) PLC; (b) GU; (c) marginal scaling at wheel path locations for PLC mix with hand placement; and (d) joints.

Figure 4 below depicts the results of the RCPT tests which also show the coulom¬¬bs values are lower for the GUL hand and slipped form placed concrete pavements compared to the GU test section.

Figure 4 below depicts the results of the RCPT tests which also show the coulom¬¬bs values are lower for the GUL hand and slipped form placed concrete pavements compared to the GU test section.

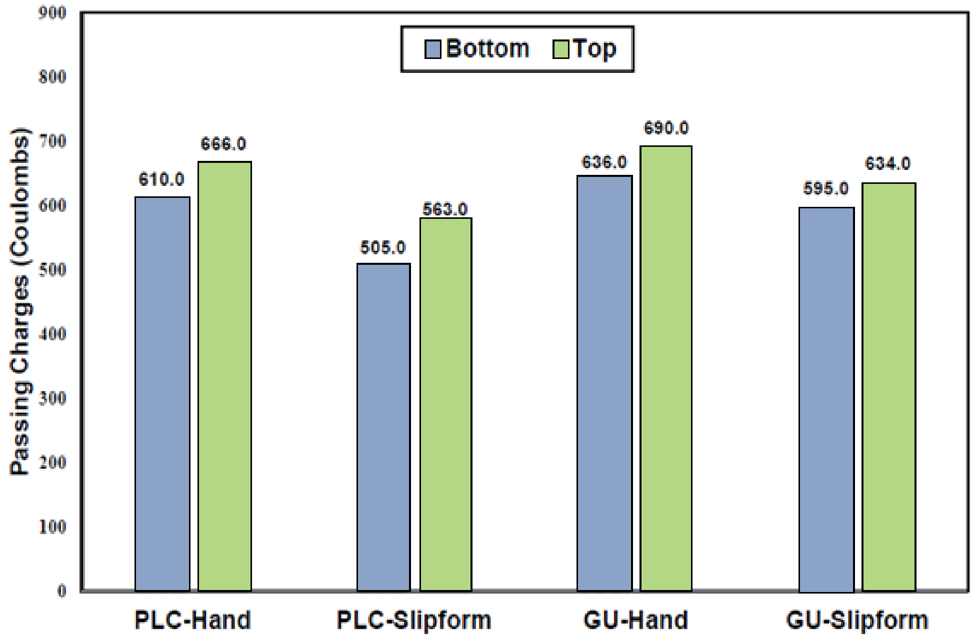


Figure 4: RCPT results for the cores taken at mid-slabs after three years

Figure 5 below shows the PLC based concrete pavement sections also outperformed the GU based concrete pavement on chloride ion penetration.

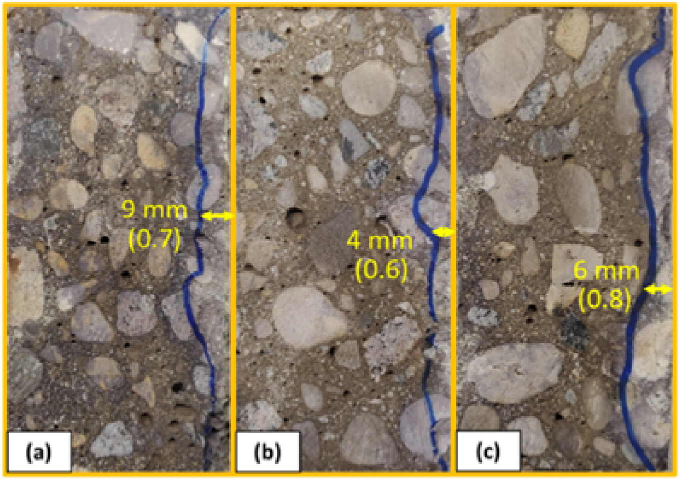


Figure 4: Exemplar chloride ions penetration depths in (a) PLC-hand placement; (b) PLC-slipform and (c) GU-slipform. Note: the values between parentheses are the standard deviations.

Figure 6 shows the GUL based concrete pavement outperformed the GU based concrete section with regard to absorption results for cores taken after 3-years of service for both pavements.

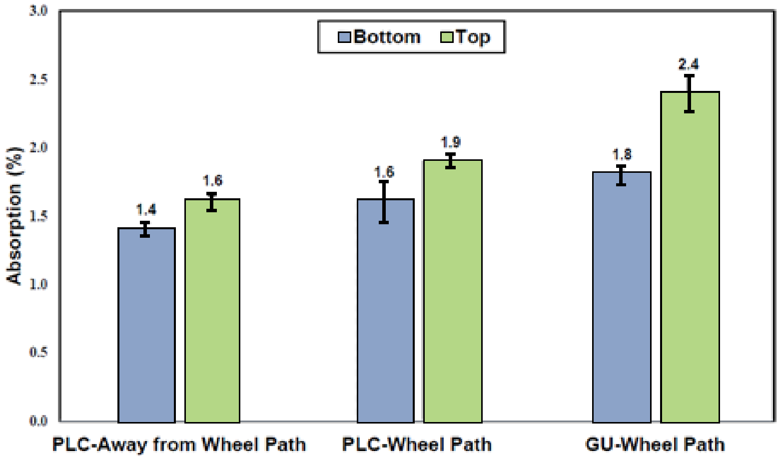


Figure 6: Absorption results for cores taken at joints after three years. (Note: Error bars represent standard deviations.)

Figure 8 from the report shows the GUL based concrete pavement was equal to or a bit better than the GU based concrete pavement for scaling resistance.

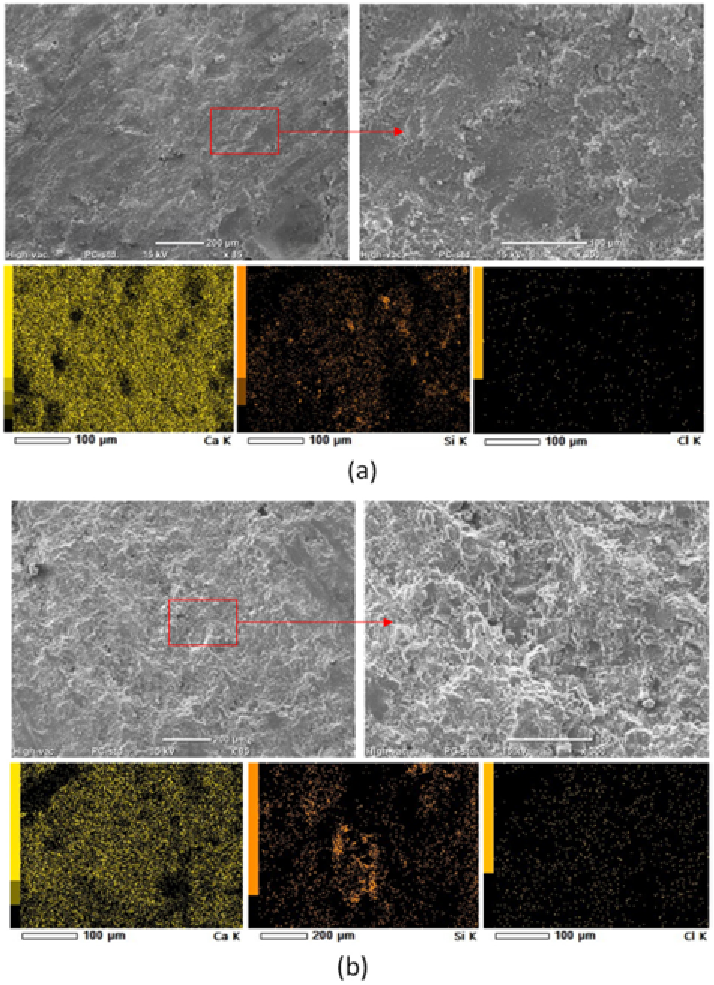


Figure 8: Scanning electron micrographs and EDX mapping after three years. (a) PLC and (b) GU.