TECHNICAL BRIEF

An Environmental Life Cycle Assessment of Portland-Limestone and Ordinary Portland Cements in Concrete

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Authors: Lindita Bushi and Jamie Meil
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Summary
Portland-limestone cement (PLC) is generally understood to have a lower carbon footprint than ordinary Portland cement (OPC). The Athena Sustainable Materials Institute performed a cradle-to-gate LCA study of both PLC and OPC to quantify the global warming potential difference between the two, and to additionally evaluate other LCA impact indicators. To demonstrate PLC replacement environmental impacts, a cradle-to-gate LCA for two typical Canadian concrete mix designs that meet ASTM requirements – a generic 35 MPa commercial mix (C1) and a 25 MPa slab mix – was completed as well.

The study demonstrates that Portland-limestone cement has lower impacts in all indicators and is about 10% better in greenhouse gas emissions.

Introduction
In 2009, the Canadian Standards Association recognized the use of Portland-limestone cement in Canadian concrete [6]. Soon after, the Cement Association of Canada (CAC) launched PLC under the name Contempra™, promoting its carbon dioxide emission savings when used in place of ordinary Portland cement, while maintaining the same level of concrete strength and durability as OPC concrete.

PLC is not new; it has been used in Europe for over 40 years. While European cement standards allow up to 35% limestone content, the Canadian standards have permitted the inclusion of up to 15% limestone in four types of PLC [6], [13]:

- 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 OPC (types GU, MH, LH, and HE), which are permitted to contain up to 5% limestone (realistically, the maximum limestone content in OPC is about 3.5% due to limits on the loss of ignition and tolerances on batch mixing). With the exception of sulfate-exposure classes S-1, S-2, and S-3, CSA A23.1-09 [6] permits the four types of PLC for use in all classes of concrete [13]. The restriction on sulfate exposure with regard to PLC is expected to be removed in the 2014 edition of the CSA A23.1. Standard PLC is an optimized intergrind of clinker (the major precursor to cement) and limestone, whereby both the clinker and a higher proportion of limestone are ground to a smaller particle size and blended together with gypsum (calcium sulfate), resulting in a more uniform and more tightly packed cement. Relative to PLC, Canadian OPC typically has a 10% higher proportion of clinker in the mix (see Table 1 below).

Table 1: *Typical PLC and OPC input mix [3], [4], [5], [6], [11], [12], [13]*

Input	Ordinary Portland Cement (OPC)	Portland Limestone Cement (PLC)
Clinker	92%	82%
Limestone	3%	13%
Gypsum	5%	5%
Total	100%	100%

By reducing the clinker (pyroprocessing) input in the cement recipe, both thermal energy use and the inevitable release of “process” related CO_2 emissions (as limestone is heated and calcined) are avoided. Much has been done in the Canadian industry to reduce energy consumption in cement manufacturing, but there are diminishing returns to increased energy efficiency efforts (conservation, technology and fuel switching) as the clinker production process is “chemical” in nature and the heat required to catalyze the pyroprocessing of limestone is unavoidable. Changing the cement recipe to PLC presents the North American concrete industry with an immediate opportunity to fundamentally change its environmental footprint.

Objective (goal and scope)

In this technical brief, the Athena Sustainable Materials Institute[1] investigates not only the potential CO_2 savings, but also a larger set of potential environmental impacts using life cycle assessment (LCA) to better understand the merits of incorporating PLC relative to OPC in concrete mix designs.

[1] The Cement Association of Canada (www.cement.ca) is a long-standing member of the Athena Sustainable Materials Institute (www.athenasmi.org); together, the two organizations have worked to advance the sustainability of the construction sector.

For the purposes of assessing the substitution of PLC for OPC, the life cycle scope is constrained to a cradle-to-gate analysis, where the cradle is the earth (extraction of raw materials) and the gate is the manufactured finished product at a ready-mixed concrete plant. In order to demonstrate the environmental impacts of PLC replacement, the Athena Institute completed the LCA for two typical Canadian concrete mix designs: a generic commercial mix (C1) and a 25 MPa slab mix, both of which meet ASTM requirements. Both mixes were provided by Lafarge Canada (see Table 2) and already employ a 25% displacement of cement inputs with fly ash (a semi-cementitious material), which is a common practice in the Canadian concrete industry.

Table 2: *Generic concrete mix designs for C1 and 25 MPa slab mixes-* [Lafarge Canada 2013]

Mix constituents and properties	**Units per m^3 of concrete**	**C1 Mix**	**25 MPa Slab Mix**
Cement (either PLC or OPC)	kg	300	206
Fly Ash	kg	100	69
Fine aggregate	kg	668	910
Coarse aggregate	kg	1020	1100
Mix water	kg	160.0	123.0
Air entraining admixture	kg	0.284	0
Water reducing admixture	kg	1.813	1.247
Total	kg	2250	2410
Mix properties			
Water-cementitious materials ratio		0.40	0.45
Cement substitution with SCM	%	25%	25%
Nominal 28-day compressive strength	MPa	35	25

The Athena Institute has completed numerous LCAs of the Canadian grey cement industry, dating back to 1993 and as recently as 2007. Similarly, the Athena Institute maintains life cycle inventory databases on aggregate production and transportation and the manufacture of ready-mixed concrete. Using these data as well as additional background life cycle inventory data on upstream materials[2], energy and transport, we are able to generate a complete cradle-to-gate environmental profile for the two concrete mix designs when using either PLC or OPC cement. Table 3 shows the LCI data sources used for this LCA. The LCA has been completed in accordance with ISO 14040/44 and follows the product category rules for concrete [2].

[2] No input cut-off criteria were applied – all materials were followed back to earth.

Table 3 Summary of LCI data sources

Material	Geography	Year	LCI data source
Ordinary Portland cement	Canada	2005-2007	Athena LCI Database [1], [8], [9]
Portland limestone cement	Canada	2005-2007	Athena LCI Database [1], [8], [9]
Fly ash	*No additional processing of fly ash was necessary for use as secondary material.*		
Fine aggregate	Canada	2005	Athena LCI Database [1]
Coarse aggregate	Canada	2005	Athena LCI Database [1]
Air entraining admixture	Europe	2005	301 Air Entrainer EPD [7]
Water reducing admixture (plasticizing)	Europe	2006	324 Plasticiser EPD [7]
Batch water	Canada	2013	Use site specific data
Ready Mixed Concrete	US adjusted to Canada	2007	Athena LCI Database [10]
Transportation	Canada, USA	2004-2008	Athena LCI Database, US Life Cycle Inventory Database (NREL)
Electricity Generation	Canada, USA	2004-2008	Athena LCI Database, US Life Cycle Inventory Database (NREL)
Fossil fuels combustion	USA	2004-2008	US Life Cycle Inventory Database (NREL)

Applying life cycle thinking entails going beyond the cement manufacturing gate itself so that we can understand how different cement types may play out through downstream life cycle stages (e.g., the manufacture of concrete) as well as highlight other environmental burdens besides carbon dioxide emissions. For the purposes of this technical brief, we employ the US EPA's TRACI[3] characterization methodology to generate life cycle impact assessment (LCIA) indicator results for the two concrete mix designs employing either PLC or OPC. The supported impact indicators are described in Table 4.

[3] TRACI – Tool for the Reduction and Assessment of Chemicals and other Impacts (v2.1, August 2012). The impact indicators comply with those stipulated as mandatory in the concrete PCR (10).

Table 4: Supported LCIA Indicators

Impact category	Unit equivalence basis (indicator result)	Source of the characterization method	Level of site specificity selected
Global warming	kg CO_2 equiv	TRACI v2.1	Global
Acidification	kg SO_2 equiv	TRACI v2.1	North America
Eutrophication	kg N water equiv	TRACI v2.1	North America
Ozone depletion	kg CFC-11 equiv	TRACI v2.1	Global
Respiratory effects	kg $PM_{2.5}$ equiv	TRACI v2.1	North America
Smog	kg O_3 - equiv	TRACI v2.1	North America
Total primary energy	MJ	CED 2001 adapted	Global
Non-renewable, fossil and nuclear	MJ		

Note – Total primary energy (TPE) consumption accounts for all forms of energy inputs while non-renewable energy consumption is a subset of TPE limited to fossil hydrocarbons and nuclear resource use.

Results

Figure 1 and Table 5 present the relative and absolute cradle-to-gate life cycle impact assessment results for the PLC and OPC. In Figure 1, the PLC LCIA results have been normalized to the OPC on a percent basis. Across all impact indicators, the PLC has a lower environmental profile relative to the OPC – these reductions are in the range of 9% to 12%. The net reduction in greenhouse gas emissions (CO_2, CH_4 and N_2O) is 9.6%.

Figures 2 and 3 present the relative cradle-to-gate life cycle impact assessment results for the C1 and 25 MPa slab mix designs when employing PLC and OPC cement. Again, both Figures normalize the PLC LCIA results to the OPC results.

For both mix designs and across all impact indicators, the PLC-based concrete results in lower environmental burdens relative to the OPC-based design mix; with the exception of ozone depletion, these reductions range from 7% to 9%. All other technical process parameters being equal, the impact of using PLC rather than OPC is proportional to the absolute quantity of cement in, or the strength class of, the concrete – relatively larger impact reductions are possible for designs employing higher cement content. Focusing specifically on global warming potential (GWP) or climate change, the net reduction in greenhouse gas emissions (CO_2, CH_4 and N_2O) is about 9% for both mixes.

Total primary energy and non-renewable energy consumption are each 8% lower for both mix designs when employing PLC rather than OPC. Around 97% of total energy use is drawn from non-renewable energy sources. Future industry efforts should be focused on decreasing the dependency on non-renewable energy and increasing the use of renewable energy sources.

The other impact category indicators vary proportionately according to energy use and, more specifically, to the content of the clinker in the cement type employed. These other impact indicators range from a few micrograms (ozone depletion potential) to a few kilograms (smog potential) per cubic meter of product. See Tables 6 and 7 for a summary of the absolute LCIA indicator results.

Figure 1: Canadian Cradle-to-Gate LCIA results for 1 kg of PLC and OPC - % basis

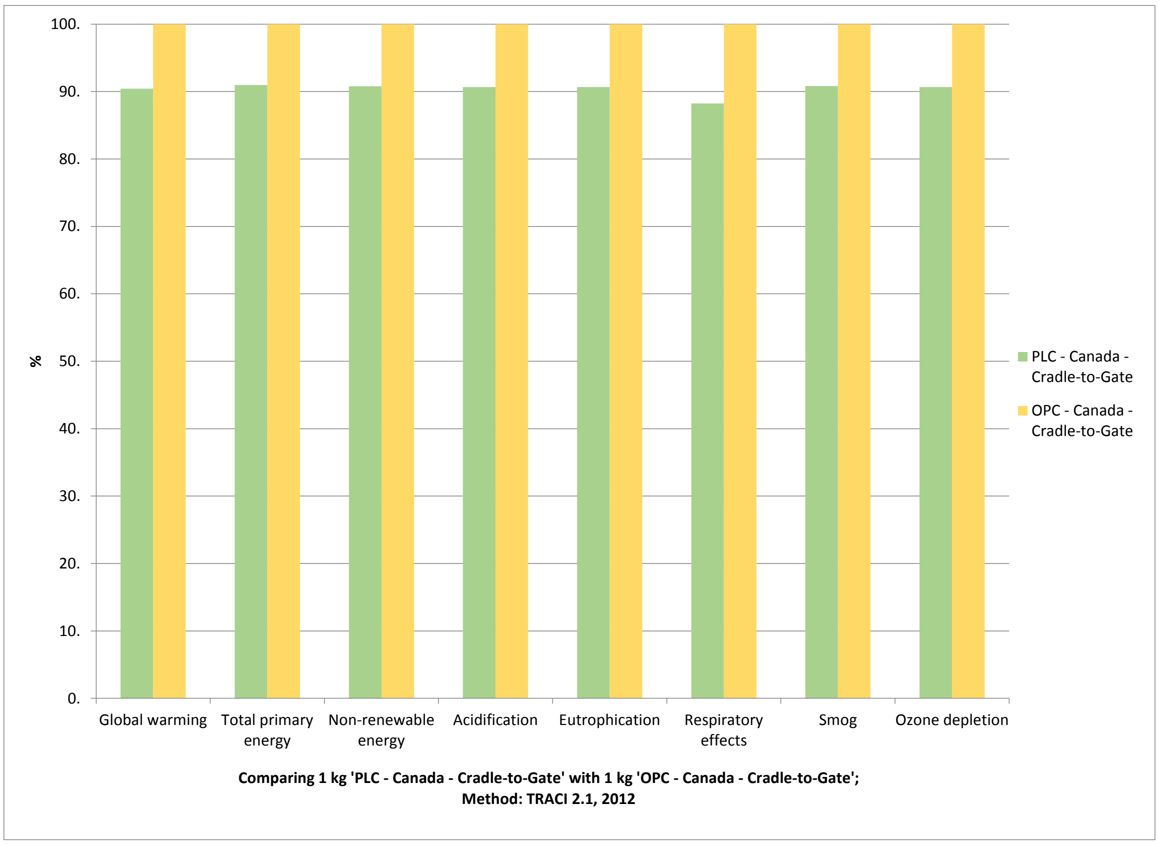

Table 5: LCIA Results Summary for PLC and OPC – 1 kg, absolute basis

Impact category	Unit	**OPC Cement-** Canada - Cradle-to-Gate	**PLC** Canada- Cradle-to-Gate
Global warming	kg CO_2 eq	0.95	0.85
Total primary energy	MJ	6.62	6.02
Non-renewable energy	MJ	6.27	5.69
Acidification	kg SO_2 eq	4.1E-03	3.7E-03
Eutrophication	kg N eq	1.3E-04	1.2E-04
Respiratory effects	kg $PM_{2.5}$ eq	3.7E-04	3.2E-04
Smog	kg O_3 eq	0.048	0.043
Ozone depletion	kg CFC-11 eq	1.1E-11	9.6E-12

Figure 2: Canadian Cradle-to-Gate LCIA results for "C1 Mix Design" using PLC or OPC – m^3, % basis

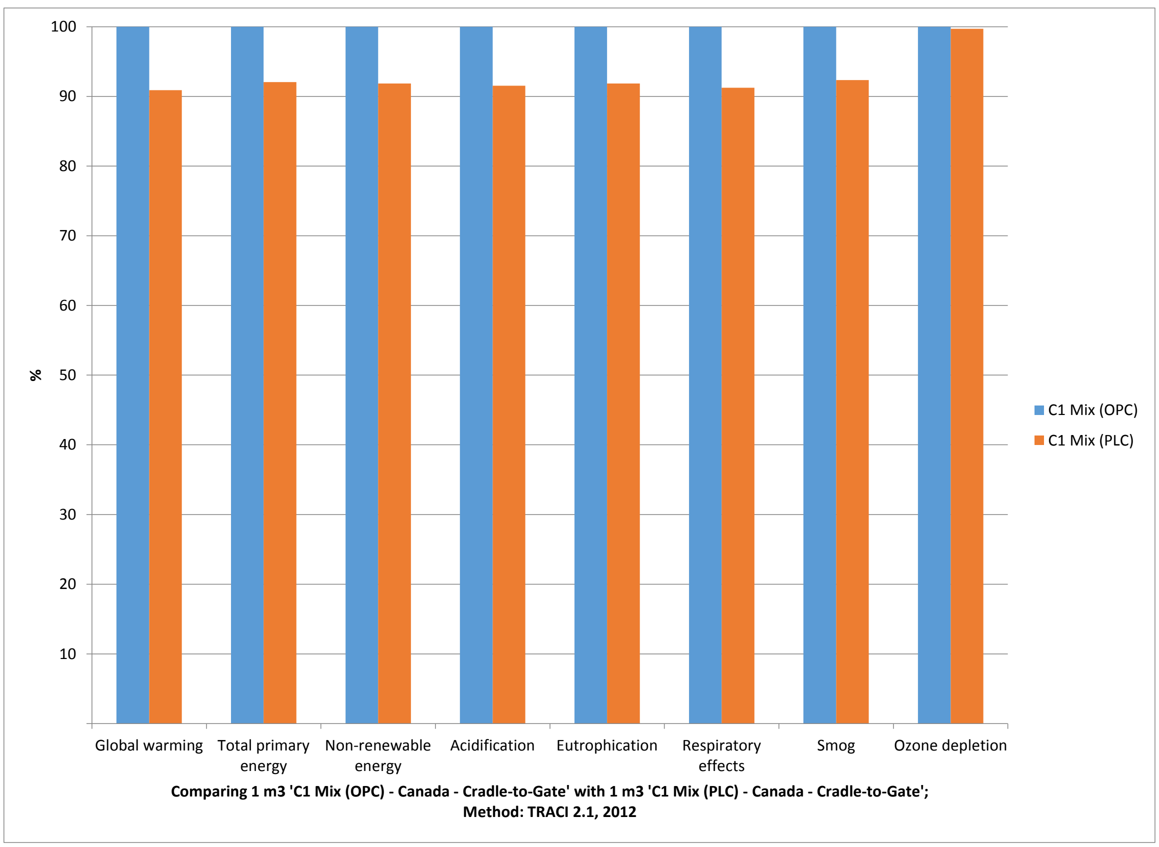

Table 6: LCIA Results Summary for C1 Mix Design using PLC and OPC– m^3, absolute basis

Impact category	Units per m3 of concrete	**C1 Mix (OPC) -** Canada - Cradle-to-Gate	**C1 Mix (PLC)-** Canada - Cradle-to-Gate
Global warming	kg CO_2 eq	299	272
Total primary energy	MJ	2258	2079
Non-renewable energy	MJ	2123	1950
Acidification	kg SO_2 eq	1.35	1.23
Eutrophication	kg N eq	0.04	0.04
Respiratory effects	kg $PM_{2.5}$ eq	0.15	0.13
Smog	kg O_3 eq	17.07	15.76
Ozone depletion	kg CFC-11 eq	9.8E-08	9.7E-08

Figure 3: Canadian Cradle-to-Gate LCIA results for “25 MPa Slab Mix Design” using PLC or OPC– m^3, % basis

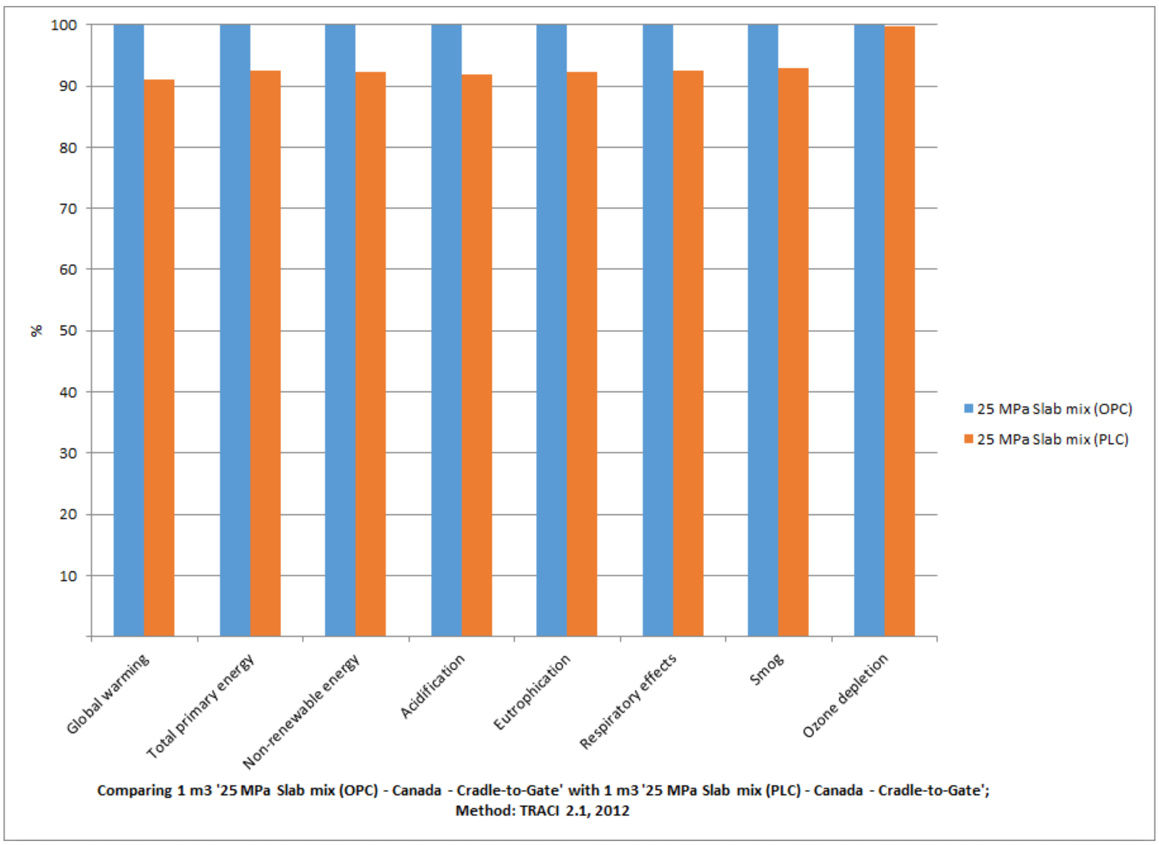

Table 7: LCIA Results Summary for 25MPa Slab Mix Design using PLC and OPC– m^3, absolute basis

Impact category	Unit	**25 MPa Slab mix (OPC) -** Canada - Cradle-to-Gate	**25 MPa Slab mix (PLC) -** Canada - Cradle-to-Gate
Global warming	kg CO_2 eq	210	192
Total primary energy	MJ	1654	1530
Non-renewable energy	MJ	1546	1427
Acidification	kg SO_2 eq	0.98	0.90
Eutrophication	kg N eq	0.03	0.03
Respiratory effects	kg $PM_{2.5}$ eq	0.12	0.11
Smog	kg O_3 eq	12.83	11.93
Ozone depletion	kg CFC-11 eq	6.6E-08	6.6E-08

Remarks

This life cycle evaluation confirms the potential CO_2 savings associated with using PLC in place of OPC in concrete mix designs. In addition, this study identifies other associated environmental benefits. Essentially, reducing the clinker portion of the cement results in an almost one-to-one benefit in reduced energy consumption and associated environmental emissions to air and water.

Clinker (cement) production remains the most fossil energy and CO_2 intensive component of the concrete supply chain (accounting for upwards of 80%); while the Canadian cement industry has taken significant steps to improve the efficiency of pyroprocessing limestone into clinker, it is apparent that the ability to displace clinker in cements (and therefore concrete) represents a large opportunity to improve the environmental performance of the entire industry. Efforts to employ greater levels of PLC in Canadian concrete and building codes – similar to those levels allowed in European codes – would go a long way to further improving the industry's environmental performance.

While the LCA work undertaken here follows good practice and international standards, this technical brief is not intended to replace an ISO-compliant LCA comparative report. Nonetheless, our method was rigorous in the use of best available data, alignment with the prevailing concrete PCR, and application of our usual internal review and benchmarking procedures.

The study represents a cradle-to-gate life cycle assessment of PLC- and OPC-based concrete mix designs and therefore does not integrate the use and end-of-life stages of the products. Consequently, the benefits of installing any of the concretes in an application are not captured in this technical evaluation.

PLC concrete mix designs are available in the Athena Institute's free LCA software tools for building and roadway designers. Our "Impact Estimator" tools can be found at calculatelca.com.

References

[1] Athena 2005, Cement and Structural Concrete Products: Life Cycle Inventory Update 2005.

[2] Carbon Leadership Forum (CLF) 2013. Product Category Rules (PCR) for ISO 14025 Type III Environmental Product Declarations (EPDs) of Concrete - Version 1.1. Seattle, WA.

[3] CAC 2009a: Portland-Limestone Cement: State-of-the-Art Report and Gap Analysis for CSA A 3000, by R. D. Hooton, M. Nokken, and M. D. A. Thomas.

[4] CAC 2009b: Backgrounder, Portland-Limestone Cement.

[5] Communication per email with CPCI technical experts, Dec 2010.

[6] CSA A23.1-09 - Concrete Materials and Methods of Concrete Construction.

[7] EFCA EPDs; 301 Air Entrainer and (http://www.efca.info/publications.html), accessed Oct, 2013.

[8] NPRI & GHG Inventory 2007- Emissions to air and water (http://www.ec.gc.ca/inrp-npri/), accessed Oct, 2013.

[9] PCA 2008, U.S. And Canadian Labor-Energy Input Survey 2007.

[10] PCA 2007, Life Cycle Inventory of Portland Cement Concrete.

[11] PCA 2003, The Use of Limestone in Portland Cement: A State-of-the-Art Review, by Peter Hawkins, Paul Tennis, and Rachel Detwiler, © Portland Cement Association 2003.

[12] PCA 2002, The Use of Limestone in Portland Cements: Effect on Thaumasite Form of Sulfate Attack, by R. Doug Hooton and Michael D. A. Thomas. PCA R&D Serial No. 2658.

[13] Thomas, M et al 2010, Field Trials of Concretes Produced with Portland Limestone Cement – New CSA cement type performs well in an aggressive environment.