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REVIEW

An overview of air emission intensities and environmental performance of grey cement manufacturing in Canada

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Abstract Air emissions generated in grey cement manufacturing originate primarily from the combustion of fossil fuels required to heat the kiln and the chemical reaction of raw materials in the pyroprocessing phase. Given that the kiln system is enclosed, air emissions generated, discharge from a single point source kiln stack. Unlike other industries, the point source kiln stack enables the cement sector to accurately monitor and record total air emissions. The largest contributors to air emissions from grey cement manufacturing are carbon dioxide (CO_2), oxides of nitrogen (NO_x), sulphur dioxide (SO_2) and dust/particulate matter (PM). In Canada, grey cement manufacturing facilities are required to annually report these emissions through the National Pollutant Release Inventory (NPRI). Since CO_2, NO_x, SO_2 and PM are the largest contributors to air emissions, and Canadian grey cement facilities are required to report these emissions, combining NPRI data with annual grey cement production data allows for the development of intensity-based environmental performance indicators. Based on data provided by NPRI, in combination with industry production, we can better understand the environmental performance of Canada's grey cement manufacturing. On the global stage, intensity-based performance measures provide a useful tool for comparison and demonstrate a strong environmental performance for grey cement production in Canada. As an energy intensive and trade exposed (EITE) grey cement manufacturing is vulnerable to unbalanced environmental policy, which may ultimately result in leakage of production and air emissions to developing countries.

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Introduction

Background

Governments around the world have been tasked with developing sound environmental policy to protect and enhance the quality of their local, regional or national ambient air quality. However, prior to developing environmental policy, decision makers must first ascertain existing air quality conditions, the relative contribution of emission sources and identify key priorities. Once this initial data gathering and prioritizing are complete, the next step is to carry out multi-criteria decision analysis (MCDA) to develop policies and ultimately legislation to effect change.

As a significant contributor to air pollution, heavy industry is accessible for policy makers given they are stationary and the emissions typically emanate from concentrated sources (i.e. through stacks) which make them easier to monitor and potentially mitigate. Consequently, many countries require monitoring of air emissions from industrial sources. In Canada, the *Canadian Environmental Act Protection Act* (CEPA 1999) requires industrial operations which exceed defined threshold limits, or are directly named, to report total annual air emissions of listed toxic substances through the national pollutant release inventory (NPRI). As a mandated sector, grey cement manufacturing facilities across Canada report air emissions into NPRI. In Canada, the NPRI program provides a valuable source of data for policy makers. As it pertains to domestic grey cement manufacturing NPRI data indicate that the industry contributes an estimated 1.4 % of total (anthropogenic) greenhouse gas emissions (GHGs) and 1 % of total air pollutant emissions in Canada (Environment Canada 2011).

As with most industrial processes, the grey cement manufacturing generates air emissions. These emissions are produced throughout the lifecycle of cement production from quarrying limestone to packaging and transporting the finished product. The largest contributors to air emissions from cement manufacturing are carbon dioxide (CO_2), oxides of nitrogen (NO_x), sulphur dioxide (SO_2) and particulate matter (PM) (WBCSD 2005). Other substances that may be emitted from cement manufacturing include volatile organic compounds, acid gases, trace metals and organic micro pollutants. However, these other substances are only emitted in trace quantities (WBCSD 2005).

On the surface, this national contribution of grey cement manufacturing to total air emissions may be significant, and may evoke the need for action. However, total emissions can be a misleading determinant of environmental performance. Total emissions provide no indication of the amount of grey cement consumed relative to other building materials, the strategic need for grey cement as a component of concrete or the long-term lifecycle benefits of concrete. Also, total emissions do not provide an accurate gauge of environmental performance of Canadian cement manufacturing in the global context.

It is important to emphasize that grey cement manufacturing is truly a global industry with plants in almost every country. One reason cement manufacturing is global is that the principal raw materials of limestone, clay and shale are common lithologies and are widely distributed in most parts of the world. As well, cement has a relatively low cost per unit weight making ground transportation an expensive externality. These factors, combined with an insatiable demand for concrete in urban development, support the need for domestic production on a global scale. According to the Cement Association of Canada (CAC), the global demand for concrete is second only to that of water (Cement Association of Canada (CAC) 2010).

In light of this, and excluding a suitable alternative to grey cement, total emissions are a poor way to measure the Canadian cement sector's environmental performance or to develop environmental policy. Rather, an intensity-based approach is needed to understand the environmental performance of Canadian cement manufacturing and to gauge performance in the global context. In terms of sustainability, developing countries face greater challenges than developed countries. By virtue of lower cost, the flow of production for many industries, and consumer demand for cost savings, production follows the cost. In developing countries, energy, labour and transport subsidies make them a prime target for production leakage. Along with production leakage emissions follow. However, in overpopulated countries (like China and India) with already intense production, the environmental and health effects are potentiated.

The first objective of this review is to develop an approach for measuring environmental performance of grey cement manufacturing, in consideration of the primary air emissions. The second step is to evaluate this performance in a global context. Drawing on global data sources, leakage research on energy intensive and trade exposed (EITE) industry, the review will lead to the role of product life cycle assessment and MCDA in informing environmental policy.

Grey cement manufacturing

Grey cement is one of the most widely used substances on the planet. It is estimated that each man, woman and child utilize an equivalent of 350 kg of cement each year (WBCSD 2005). In 2008, global cement production was approximately 2.8 billion tonnes (WBCSD 2011). Despite the incredible need and consumption of cement for use in concrete to build housing and infrastructure, there is also an awareness of the environmental sustainability issues associated with the manufacturing process (WBCSD 2005). Grey cement manufacturing involves four broad sets of activities: quarrying; raw materials preparation; clinker production and grinding and distribution (Fig. 1).

In quarrying, limestone and other materials are extracted by drilling and blasting. The quarry is typically located at or near the cement manufacturing facility to keep transportation costs low. Following extraction, the quarried material is reduced in size by a crusher. These raw materials are then transported to the cement plant by truck, conveyor or rail car for preparation.

At the cement plant, the limestone, clay and other raw materials are mixed and homogenized. This mixture is then further pulverized in the raw mill into a fine ground material. In the next step, clinker production, this fine ground material is heated in a kiln to 1,450–1,500 °C where it becomes transformed into a molten product called clinker (this step is referred to as pyroprocessing). The clinker is cooled as it exits the kiln system and stored in silos. The clinker is finely ground and mixed with gypsum to become cement. In addition to gypsum, ground limestone and other supplemental cementitious materials may be added to the mix, such as fly ash or slag. The final cement product is then distributed in bags or a as bulk powder by truck, ship and rail car.

Air emissions and related effects

Air emissions generated in grey cement manufacturing originate primarily from the combustion of fossil fuels

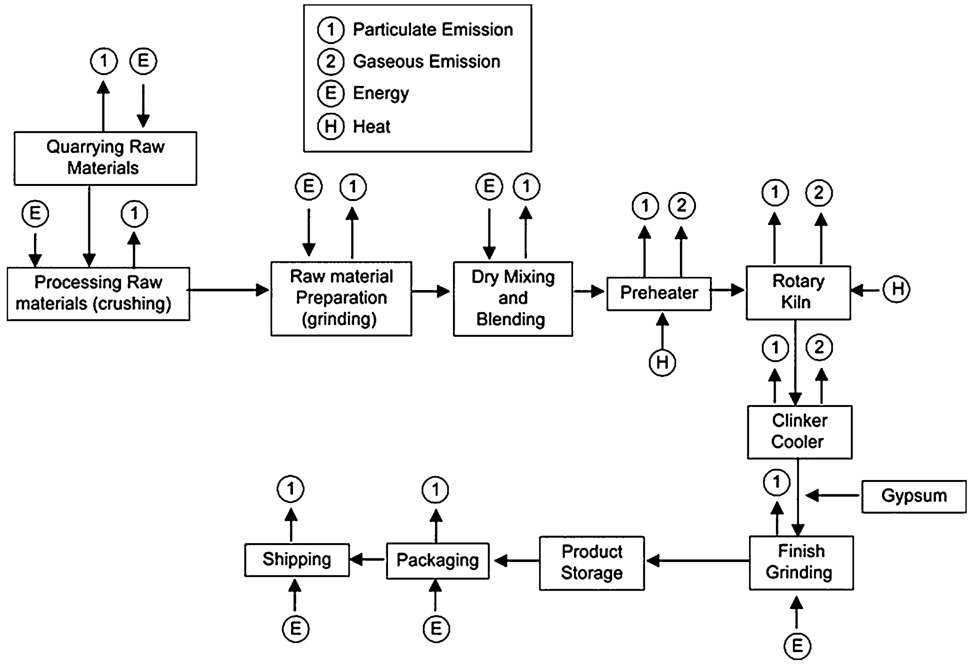

Fig. 1 Grey cement manufacturing process flow diagram

required to heat the kiln and the chemical reaction of raw materials in the pyroprocessing phase. Given that the kiln system is enclosed, air emissions discharge from a single point source kiln stack. Unlike other industries, the point source kiln stack enables the cement sector to accurately monitor and record total emissions. The largest contributors to air emissions from grey cement manufacturing are carbon dioxide (CO_2), oxides of nitrogen (NO_x), sulphur dioxide (SO_2) and dust/particulate matter (PM).

Carbon dioxide

The coal example provided in Table 1 shows the reaction combustion of methane in the presence of oxygen that produces CO_2 and water. The calcining process thermally decomposes $CaCO_3$ to CaO and CO_2. Typically, Portland cement contains the equivalent of about 63.5 % CaO. Consequently, about 1.135 units of $CaCO_3$ are required to produce 1 unit of grey cement, and the amount of CO_2 released in the calcining process is about 500 kg/tonne of grey cement produced. Total CO_2 emissions from the pyroprocess depend on energy consumption and generally fall in the range of 850–1,135 kg of CO_2 per tonne of clinker. Potential health effects related to carbon dioxide are presented in Table 1.

Oxides of nitrogen

Oxides of nitrogen (NO_x) are generated during fuel combustion by oxidation of chemically bound nitrogen in the fuel and by thermal fixation of nitrogen in the combustion air. As described in Table 1, there are three principal mechanisms for NO_x formation in grey cement manufacturing operations: thermal NO_x; fuel NO_x and prompt NO_x. Thermal NO_x results from the oxidation of nitrogen in air at temperatures above 1,200 °C. As flame temperature increases, the amount of thermally generated NO_x increases. In cement manufacturing operation, thermal NO_x is only generated at significant amounts within the kiln itself, but not at significant amounts within the precalciner. Thermal NO_x results from the oxidation of molecular nitrogen in air at high temperature. This phenomenon occurs in and around the flame in the burning zone of a cement kiln at a temperature greater than 1,200 °C. The three principal reactions (the extended Zeldovich mechanism) that produce thermal NO_x is

$$N_2 + O \rightarrow NO + N$$
$$N + O_2 \rightarrow NO + O$$
$$N + OH \rightarrow NO + H.$$

Fuel NO_x results from the oxidation of nitrogen in fuel and occurs at any temperature. Fuel NO_x will be generated within a cement kiln and within a precalciner, as well as within any ancillary device (transportation equipment, coal mill, etc.) where fuels may be combusted. The amount of NO_x generated from fuel increases with the quantity of nitrogen in the fuel. In the grey cement manufacturing process, NO_x is generated in both the burning zone of the kiln and the burning zone of a precalcining vessel. Fuel use

Table 1 Major air emissions from grey cement manufacturing and associated effects

Pollutant	Formation	Human health risks	Environmental risks
Carbon dioxide (CO_2)	Combustion reaction of fuel (e.g. Coal): $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ Calcination of Limestone: CaCO3 → CaO + CO2 Approximately 40 % of CO_2 emissions from grey cement manufacturing are generated through fuel combustion; approximately 60 % are generated through the limestone calcining process	CO_2 is not a toxic substance, although at high concentrations (in excess of 100× normal outdoor air concentrations of 360 PPM) it can act as an asphyxiant	There is broad consensus in the scientific community that the earth's atmospheric CO_2 concentration has increased as a result of human industrial activity over the past 200 years, and this increase is linked to climate change
Oxides of Nitrogen (NO_x)	Thermal: $N_2 + O \rightarrow NO + N$ Fuel: $N + O_2 \rightarrow NO + O$ Prompt: $N + OH \rightarrow NO + H$ NO_x are generated during fuel combustion by oxidation of chemically bound nitrogen in the fuel (Thermal/Fuel NO_x), and by the thermal fixation of nitrogen in the air to hydrocarbon radicals ('Prompt' NO_x)	NO_x can react with atmospheric ammonia, VOCs and moisture to form particles such as Ozone that can damage lung tissue if inhaled	Atmospheric NO_x reacts with water molecules to form acid rain, which damages ecosystems, buildings and infrastructure. Also strongly associated with smog formation
Sulphur dioxide (SO_2)	$2CaSO_4 + 2\ SiO_2 + C \rightarrow 2\ CaSiO_3 + 2\ SO_2 + CO_2$ Sulphur dioxide (SO_2) may be generated both from the sulphur compounds in the raw materials during pyroprocessing, and from the combustion of sulphur-containing fuels such as coal and petroleum products	Concentrations of ambient SO_2 of as low as 1 ppm have been linked to temporary reduction in lung function and difficulty breathing. SO_2 is also strongly associated with incidence of bronchitis and other respiratory illnesses, particularly amongst children. Also an eye irritant	Atmospheric SO_2 reacts with water molecules to form acid rain, which damages ecosystems, buildings and infrastructure. Also strongly associated with smog formation
Coarse Particulate Matter (PM_{10})	Compounds commonly associated with particulate matter (PM) include Sulphate (SO_4), Nitrate (NO_3), elemental carbon, and various organic compounds (e.g. PAHs, PNAs) and heavy metals (lead, zinc, copper, nickel etc.), along with suspended water particles	A bronchial/respiratory irritant; exposure is linked to bronchitis, chronic cough and respiratory symptoms, reduced lung function, and respiratory and cardiac hospital admissions	Harmful compounds commonly associated with PM include Sulphate (SO_4), Nitrate (NO_3), elemental carbon, and various organic compounds (e.g. PAHs, PNAs) and heavy metals (lead, zinc, copper, nickel etc)
Fine Particulate Matter ($PM_{2.5}$)	The largest emission source of PM in cement manufacturing is the pyroprocessing system (includes the kiln and clinker cooler exhaust stacks), though there are emissions at every production stage, from quarrying and grinding to packaging	The same health risks as Coarse PM, though Fine PM also typically contains a higher proportion of toxic metals and acid species, and due to its size and shape it can penetrate more deeply into the respiratory tract	Harmful compounds commonly associated with PM include Sulphate (SO_4), Nitrate (NO_3), elemental carbon, and various organic compounds (e.g. PAHs, PNAs) and heavy metals (lead, zinc, copper, nickel etc)

affects the quantity and type of NO_x generated. A third and generally less important source of NO_x formation is Prompt NO_x, which forms from the rapid reaction of atmospheric nitrogen with hydrocarbon radicals. Prompt NO_x is generally very minor compared to the overall quantity of NO_x generated from cement manufacturing operations.

Due to the fact that NO_x is only present when in combination with a variety of other combustion-related pollutants, the specific adverse health effects of NO_2 are somewhat difficult to gauge—health risks may stem from the molecule itself, or its reaction products (i.e. Ozone (O_3) and secondary particles). A 2003 WHO report states that 'the levels encountered in the ambient outdoor air, direct effects of NO_2 alone on the lungs (or any other system) are minimal or undetectable.' A 2003 EPA report states that NO_2 exposure is associated with eye, nose and throat irritation, with extremely high-dose indoor exposure associated with pulmonary edema and diffuse lung injury. Asthmatics, young children and individuals with pre-existing lung diseases are thought to be at a higher risk for respiratory harm related to NO_2 exposure, though evidence remains inconclusive. The greater threat posed by NO_2 is almost certainly its propensity to transform into nitric acid, one of the principal components of acid rain. Acid rain is damaging to plants and wildlife, and in particular to aquatic ecosystems.

Sulphur dioxide

Sulphur dioxide (SO_2) may be generated both from the sulphur compounds in the raw materials and in the fuel. Sulphide or elemental sulphur contained in raw materials (e.g. limestone) is 'roasted' or oxidized to SO_2 during pyroprocessing where sufficient oxygen is present and the material temperature is in the range of 300–600 °C (PCA 2013). In fuel, the sulphide or elemental sulphur (e.g. coal) is oxidized to SO_2 at temperatures in the range of 300–600 °C. However, the alkaline nature of the grey cement provides for direct absorption of SO_2 into the product, thereby, mitigating the quantity of SO_2 emissions in the exhaust stream. Depending on the process and the source of the sulphur, SO_2 absorption ranges from about 70–95 %. Unless the fuel source is heavily contaminated, on mass balance, the main source of SO_2 emissions for modern kilns comes from the raw materials.

Unlike NO_x emissions, SO_2 generation is much more variable (even within the same kiln technology) as it is highly affected by the raw materials used in the manufacturing process, and, therefore, the geographical locations of the plants. Within Canada, cement kilns generate low levels of SO_2, as the sulphur content in limestone tends to be low in Western Canada, increasing in concentration in Central Canada (Cement Association of Canada (CAC) 2010). Even within Central Canada, however, while sulphur concentrations in limestone are considerably higher than in Western Canada, there remain distinct quarry to quarry variations (Cement Association of Canada (CAC) 2010).

Sulphur dioxide is a particularly foul-smelling air pollutant associated with a wide range of negative environmental and human health impacts. At low levels of outdoor exposure, humans are generally able to block the majority of SO_2 from entering the respiratory system, as it is absorbed by the natural mucous layer in the throat and nose. However, concentrations of ambient SO_2 of as low as 1 ppm have been linked to temporary reduction in lung function and difficulty breathing. The 1996 APHEA project on ambient air pollution in Paris notably found a highly significant correlation between the daily ambient concentration of SO_2 and both hospitalizations and mortality from respiratory causes. SO_2 is also strongly associated with incidence of bronchitis and other respiratory illnesses, particularly in children.

In light of recent findings suggesting that the health risks associated with SO_2 exposure are more severe than was originally thought, in 2011 the WHO revised their 24 h guideline value for SO_2 exposure from 125 down to 20 $\mu g/m^3$.

Particulate matter (PM)

Compounds commonly associated with particulate matter (PM) include Sulphate (SO_4), Nitrate (NO_3), elemental carbon and various organic compounds (e.g. PAHs, PNAs) and heavy metals (lead, zinc, copper, nickel etc.), along with suspended water particles. Though the specific chemical composition of Particulate Matter may vary widely, it is by its very nature a respiratory and bronchial irritant, with the ability of the lung to clear itself of inhaled particles being the primary determinant in PM's specific health risks. This in turn varies based on the average size and composition of inhaled particles, with 'coarse' PM_{10} (particulate matter with an aerodynamic diameter of 2.5–10 μm) less strongly associated with incidence of cardiopulmonary or lung cancer than the pernicious 'fine' $PM_{2.5}$ particles (diameter of less than 2.5 μm). Fine particulate matter typically contains a higher proportion of toxic metals and acid species, and due to its size and shape it can penetrate more deeply into the respiratory tract.

Numerous studies have also indicated a strong relationship between both PM_{10} and $PM_{2.5}$ exposure and bronchitis, chronic cough and respiratory symptoms, reduced lung function and respiratory and cardiac hospital admissions. Predictably, those with pre-existing lung or respiratory conditions, young children and the elderly are thought to be at a higher risk for PM-related injury or premature death.

Table 2 Portland grey cement manufacturing operations in Canada (Cement Association of Canada (CAC) 2010)

Company	Plant	# of kilns	Process	Year Began or Modernized	Fuel[a]	Clinker Capacity *000 tonnes*
Lafarge	Brookfield, NS	2	Dry	1964	C, A	520
			Dry	1978		
Lafarge	St. Constant, QC	2	Dry	1966	K, A	956
			Dry	1975		
Ciments Quebec	St. Basile, QC	1	Dry (precalciner)	1982	C, O, G, A	1,150
				2002–2008		
Colacem	Calumet, QC	1	Dry	2004[b]	C	265
Holcim Canada	Joliette, QC	4	Dry	1965	C, K, A	900
			Dry	1965		
			Dry	1970		
			Dry	1973		
Lafarge	Bath, On	1	Dry (preheater)	1973	C, K, G	1,064
Essroc	Picton, On	2	1 Dry	1965	C, K, G	1,250
			1 Dry (preheater)	1975		
Holcim Canada	Mississauga, On	1	1 Dry (preheater/precalciner)	1988	C, A	1,380
St. Marys	Bowmanville, ON	1	1 Dry (preheater & precalciner)	1991	C, K	1,966
Lafarge	Woodstock, On	2	Wet	1956	C, K	526
				1957		
St. Marys	St. Mary's, ON	1	Dry (preheater)	1976	C, K	754
Lafarge	Exshaw, AB	2	1 Dry	1976	C, G	1,209
			1 Dry (preheater/precalciner)	1981		
Lehigh Cement	Edmonton, AB	1	1 Dry (precalciner)	1997	C, G	1,082
Lafarge	Kamloops, BC	1	1 Dry	1970	C, K, A	193
Lafarge	Richmond, BC	1	1 Dry (preheater/precalciner)	1999	C, G, K, A	1,260
Lehigh Cement	Delta, BC	1	1 Dry (preheater)	1978/1992	C, G, O, A	1,207

[a] *C* coal, *G* gas, *K* petroleum coke, *A* Alternative source (e.g. tires, biosolids, construction and demolition removals, etc., *O* Oils (e.g. Bunker C fuel oil)

[b] While starting operations as a cement manufacturing facility in 2004, the Colacem facility is not a new, modern cement facility, but rather an upgraded former brick manufacturing kiln

There is a significant body of scientific research investigating the risks posed by CO_2, NO_x, SO_2 and PM to human health and the health of natural ecosystems. While some of these alleged risks remain contentious, there is certainly broad agreement that at sufficiently high ambient concentrations, each of these pollutants can lead to adverse health outcomes and that regulating industrial emissions of these pollutants should be a priority for governments.

Environmental performance of Canadian grey cement manufacturing industry

Landscape

According to Cement Association of Canada (CAC) (2010), there are 15 grey cement plants and one white cement plant operating in Canada. In 2008, the Canadian cement industry produced 15 million tonnes of cement (valuing over $1.7 billion) and provided more than 2,000 jobs (Cement Association of Canada (CAC) 2010). Based on data from 2008, 65 % of Canada's cement is produced for the Canadian market and 35 % is exported to the United States (Cement Association of Canada (CAC) 2010). Combined with the concrete industry, cement and concrete collectively employ 27,000 Canadians and contribute over $3.2 billion to Canada's gross domestic product (Cement Association of Canada (CAC) 2010). As demonstrated in Table 1, Canada's cement manufacturing operations only utilize energy efficient dry kiln technology. In comparison with the US, Canada's cement sector is relatively modern and efficient. In 2008, the last of Canada's wet kiln facilities (Lafarge Woodstock) suspended operations. Meanwhile, as of the end of 2007, nearly 30 % of all cement

Table 3 Grey cement performance indicators (Cement Association of Canada (CAC) 2010)

Year	2003	2004	2005	2006	2007	2008	2009	2010
Production indicators								
Clinker production (Mt)	13.20	13.81	13.88	14.12	13.75	12.45	9.58	10.81
Cement production (Mt)	15.13	16.05	16.47	16.55	16.29	15.00	11.54	13.48
Clinker to cement ratio (%)	87	86	84	85	84	83	83	80
CO_2 and climate change indicators								
Direct CO_2 emissions (Mt CO_2)	11.81	12.51	12.61	12.77	12.30	11.04	8.39	9.53
Direct CO_2 emissions intensity (kg CO_2/tonne cement)	781	779	766	772	755	736	727	707
Air quality indicators								
Total NO_x emissions (tonnes/year)	40,431	43,415	44,295	31,108	32,004	28,908	24,350	25,669
NO_x emissions intensity (kg/tonne cement)	2.67	2.71	2.69	1.88	1.96	1.93	2.11	1.90
Total SO_2 emissions (tonnes/year)	37,359	42,768	38,355	31,992	28,381	22,309	17,773	16,760
SO_2 emissions intensity (kg/tonne cement)	2.47	2.67	2.33	1.93	1.74	1.49	1.54	1.24
Particulate matter (PM) emissions (tonnes/year)	3,927	4,382	4,369	4,572	5,330	4,250	3,280	2,819
PM emissions intensity (kg/tonne cement)	0.26	0.27	0.27	0.28	0.33	0.28	0.28	0.21

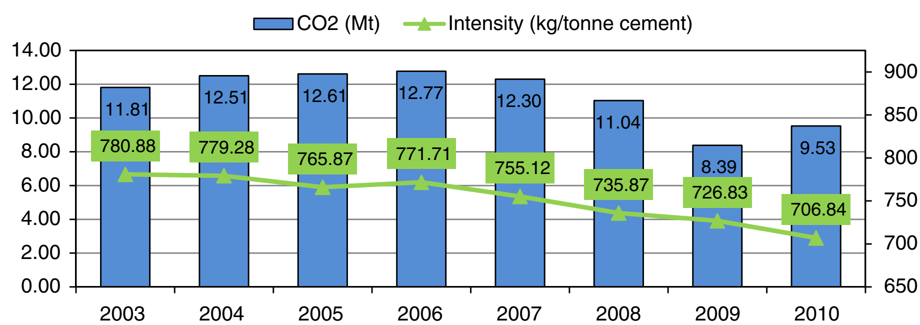

Fig. 2 Total CO_2 and CO_2 intensity (2003–2010)

kilns operating in the United States were less efficient wet kilns, constructed prior to 1960 (Cement Association of Canada (CAC) 2010) (Table 2).

Environmental performance indicators

The Cement Association of Canada's *2012 Environmental Performance Report* provides total production numbers for grey cement, CO_2, NO_x, SO_2 and PM totals for 2003–2010 (see Table 3). In addition to total values, the report also provides emission intensity values for CO_2, NO_x, SO_2 and PM. These emission intensity values are provided in kilograms per tonne of cement. Table 3 forms the basis of discussion on the individual air quality parameters as well as the subsequent figures.

Intensity-based environmental performance (2003–2010)

Total cement production reflects historic economic cycles. During the housing boom period in Canada and the United States cement production peaked at 16.55 Mt. When the crash occurred in 2008, the subsequent cement production in 2009 was down five million tonnes from 2006. Interestingly, the clinker to cement ratio has trended down from 87 % in 2003 to 80 % in 2010, reflecting increased use of ground limestone and supplemental cementitious materials such as fly ash or slag.

CO_2 emissions

Since 2003, total annual CO_2 emissions from the Canadian grey cement manufacturing sector have varied from 8.39 Mt to 12.77 Mt (Fig. 2). Given the primary formation of CO_2 is relative to the amount of fuel consumed and $CaCO_3$ calcined, total CO_2 emissions increase with total cement production. However, the CO_2 intensity demonstrates a decrease of 9.5 % from 2003 to 2010 (Fig. 2).

NO_x emissions

Since 2003, total annual NO_x emissions from the Canadian grey cement manufacturing sector have varied from 24,350 tonnes to 44,295 tonnes (see Fig. 3). Unlike CO_2, there are

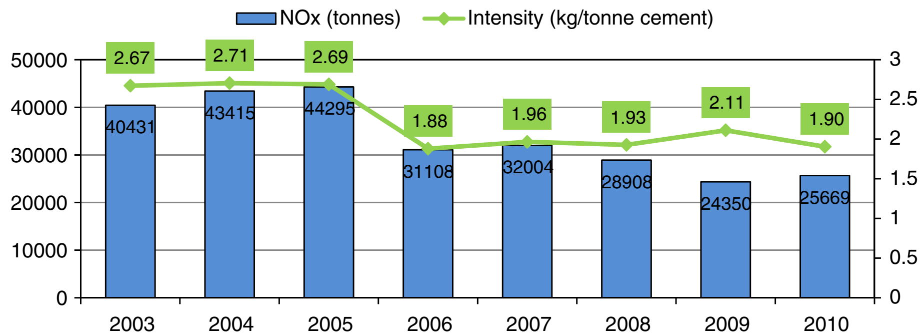

Fig. 3 Total NO_x and NO_x intensity (2003–2010)

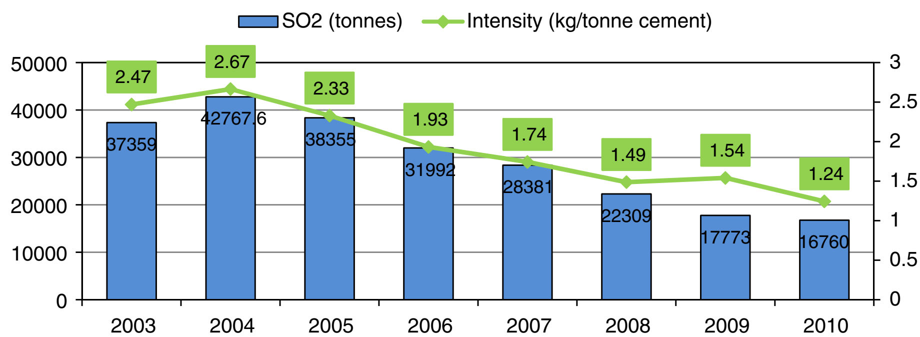

Fig. 4 Total SO_2 and SO_2 intensity (2003–2010)

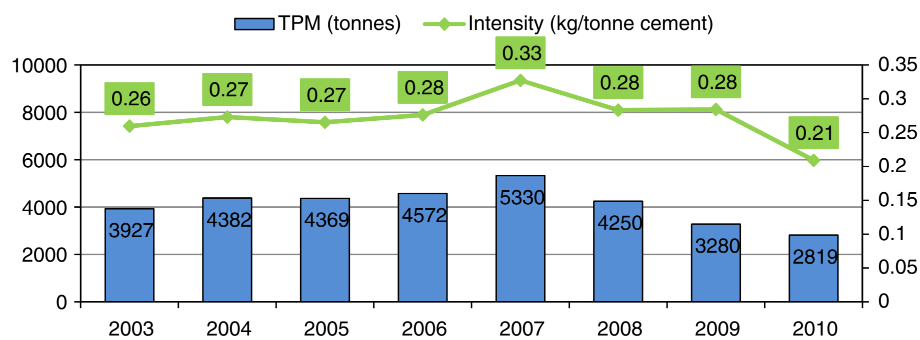

Fig. 5 Total PM and PM intensity (2003–2010)

three modes of NO_x formation and fuel type and technology can strongly influence the amount of NO_x generated. As such, total NO_x production may not be as directly correlated to total cement production. However, the NO_x intensity has also decreased from 2003 to 2010. In 2003, NO_x intensity was 2.67 kg/tonne cement, and in 2010, NO_x intensity was 1.90 kg/tonne cement, a 28 % decrease.

SO_2 emissions

Since 2003, total annual SO_2 emissions from the Canadian grey cement manufacturing sector have varied from 16,760 to 42,767 tonnes (see Fig. 4). In spite of total grey cement production total SO_2 shows as downward trend from 2003 to 2010. This is strongly reinforced by SO_2 intensity which has dropped significantly 2003 to 2010. In 2003, SO_2 intensity was 2.47 kg/tonne cement, and in 2010, SO_2 intensity was 1.24 kg/tonne cement, a 49.8 % decrease.

PM emissions

Since 2003, total annual PM emissions from the Canadian grey cement manufacturing sector have varied from 2,819 tonnes to 5,330 tonnes (see Fig. 5). As with CO_2, PM emissions fluctuate with total grey cement production as demonstrated between 2003 and 2010. However, the intensity of PM has generally remained consistent fluctuating between 0.21 kg/tonne cement 0.33 kg/tonne cement.

Discussion

Interpretation

Based on a review of total emissions and intensities for CO_2, NO_x, SO_2 and PM, it is clear that total emissions are not a reliable way to measure grey cement manufacturing environmental performance. Total emissions generally fluctuate with total production and fail to provide a benchmark, whereby performance can be measured. For intensity-based values, with the exception of PM, there is a downward trend from 2003 to 2010. It is unclear why PM intensity has not also notably decreased during this timeframe given the implementation of fabric filter bag houses at many of the facilities. However, in efforts to reduce CO_2 emissions facilities have attempted to supplant fossil fuels with alternative and renewable fuels. Cristea and Cinti (2010) suggest that the use of alternative and renewable may actually increase PM.

The reduction in CO_2 intensity for cement can be attributed to three factors: (1) increased use of alternative and renewable fuels which supplant fossil-based fuels, (2) incorporation of supplemental cementitious materials (e.g. fly ash, slag) which reduce clinker content and (3) increase use of ground limestone to further reduce the clinker content in cement. Reduction in NO_x intensities results from process modification and the implementation of control measures such as selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR). Interestingly, using end of life tires for fuel can reduce NO_x emissions by 15–30 % (Corti and Lombardi 2004).

Similar to NO_x, the decrease in SO_2 intensity is attributable to both process and secondary control measures. Managing combustion efficiency and using excess oxygen in the kiln have a significant impact on fuel-based SO_2. Lime injected into the kiln system reacts with SO_2 to form calcium sulphate which is generally incorporated into the clinker product. Wet scrubbing technology can also be used to remove SO_2 from the exhaust gases in the stack (Bradley et al. 2011).

Despite this improved environmental performance, the latest information from Environment Canada (2011) indicates that domestic grey cement manufacturing is responsible for 1.4 % of total (anthropogenic) GHGs and 1 % of total air pollutant emissions in Canada. Consequently we need to expand the picture to flesh out what these emissions means nationally and where Canadian grey cement manufacturing is situated in the context of global environmental performance.

Global context

According the World Health Organization (WHO 2011), and looking primarily at PM pollution, Canadian air quality is the third best in the world. Developing countries such as China and India are considerable worse off. According to He et al. (2002), in the early 1990s less than 1 % of the 500 cities in China reach Class I of the Chinese National Ambient Air Quality Standards (CNAAQS)[1]. In India, the country-wide annual average for PM 10 is over 100 $\mu g/m^3$, which is five times the recommended limit of 20 $\mu g/m^3$ (WHO 2011).

[1] Class I of CNAAQS are comparable to good air quality standards in developed countries.

Table 4 Comparison of Canadian and China's environmental performance intensities (2008)

Country	Canada	China
Air quality indicators emissions intensity (kg/tonne cement)		
CO_2	736	642.75
NO_x	1.93	1.38
SO_2	1.49	0.87
PM	0.28	2.54

With the exception of CO_2, the emissions intensities for NO_x, SO_2 and PM fall within the ranges provided by the European Integrated Pollution Prevention Control Bureau (WBCSD 2005). Cement CO_2 intensity in Europe has been below 700 kg/tonne of CO_2, since year 2000. Although clinker intensity is comparable to that of the Canadian cement sector. The reason for the disparity in cement CO_2 intensity between Canada and Europe is likely due to the higher proportion of blended cements that can take advantage of more ground limestone and supplemental cementitious materials, reducing the amount of clinker in the product (WBCSD 2011).

Accurate emission intensities from developing countries such as China are much harder to come, by given, there are significant data gaps, data inaccuracies and production and emissions coverage by CSI are limited to member companies with new and modernized plants in the region (WBCSD 2011). However, an inventory completed by Lei et al. (2011) at Tsinghau University provides total cement production and emissions data from 2008 (Table 4).

Although Table 4 indicates that national intensities for CO_2, NO_x and SO_2 are lower in China, it is difficult to reconcile this better performance with the fact the China produces one-third of its cement from vertical shaft kilns (Lei et al. 2011). Vertical shaft kilns are the oldest, dirtiest and least efficient kiln systems in cement manufacturing. There are no shaft kilns in Canada and the last wet kiln was suspended in 2008. Given that the Canadian cement manufacturing industry has a modern fleet of plants one would expect to see better environmental performance. With respect to PM intensity, this considerable difference aligns with both what would be expected given the mixed kiln technology and the WHO air quality ranking of China.

In terms of production, the Canadian grey cement manufacturing sector is easy eclipsed by China and India as the largest world-wide producers. In 2008, China alone produced 1.38 billion tonnes of cement (European Chamber 2009). China's investment into cement manufacturing in 2009 suggests that current (2011) overcapacity is in excess of 1 billion tonnes (European Chamber 2009). The European Chamber (2009) indicates that the overcapacity in the cement sector, compared with Chinese overcapacity in the aluminium industry, is thought to be caused by market forces, subsidized energy prices, easy access to technology and funding and stimulus spending.

Consequently, Canadian cement manufacturers are under considerable competitive strain from Asia-based producers. In Canada, higher production costs of result from increased environmental regulatory control, expensive fuel and labour. Based on the Economic Chamber's projections, the entire Canadian cement production as of 2008 could be replaced by 1.5 % of China's overcapacity. It is possible the reason that complete market takeover has not already occurred is that cement has a low cost per unit weigh ratio, making ground transportation very expensive.

Energy intensive & trade exposed (EITE) industry and leakage

Over the past decade, concerns around greenhouse gases, particularly CO_2, have prompted governments at regional, national and international levels to develop and implement emissions reduction programs. The cement industry is acutely aware of these measures given it contributes approximately 5 % of global CO_2 emissions (WBCSD 2011). In 2005, the European Economic Commission (EEC) introduced the European Union Emissions Trading Scheme (EUETS). In 2007, select Canadian provinces and US states signed onto the western climate initiative (WCI) with the purpose of developing a North American emissions trading system (cap and trade). In 2008, the province of British Columbia in Canada implemented a carbon tax on fuel emissions and in 2011 Australia followed suit with introducing their own carbon tax.

A few years after the implementation of EUETS, the European Commission recognized an oversight with the program. EITE industry in countries covered by EUETS was at a competitive disadvantage to foreign imports from industry in unregulated countries. The resulting effect was CO_2 emissions leakage. In 2009, the European Commission issued a directive identifying and allowing protection for sectors with trade exposure to countries not subject to EUETS (EEC 2010). In June 2010, the WCI released a report on the risk of emissions leakage associated with electricity imports and exports from non-WCI jurisdictions calling for first-jurisdictional delivery to mitigate these effects. These actions taken by EUETS and WCI recognize that emissions leakage must be thoroughly considered in order to genuinely reduce global CO_2 emissions.

Applying the concept of emissions leakage to NO_x, SO_2 and PM follows the same logic. If stringent regulation increases cement production costs locally, the production may be shifted to a non-regulated country and cement imported. The result would be local decrease in emissions because production decreases, while global emissions remains unchanged, if not increased due to poorer standards in developing nations. Simply put, air emissions leakage refers to the change in emission A externally ($\varDelta Ax^{ext}$) divided by the absolute value of local or internal emissions reductions ($\varDelta Ax^{int}$). This result is then expressed to denote relative percent leakage (L). For example, if the $L = 25$ % this suggests that Ax emissions have increased by 25 % in the non-regulated country (Chen 2009).

$$L = \frac{\Delta \mathrm{Ax}^{\mathrm{Ext}}}{|\Delta \mathrm{Ax}^{\mathrm{Int}}|} * 100\%. \tag{1}$$

Studies on Annex B countries complying with their commitment to the Kyoto Protocol suggest that CO_2 emissions leakage will range from 5 to 20 % (Kallbekken et al. 2007; Barker et al. 2007). In evaluating the EUETS transition path to 2020, Bernard and Vielle (2009) indicate some industries may incur CO_2 emission leakage over 10 %. Disparity between regional greenhouse gas initiative (RGGI) states and non-RGGI states in the US demonstrate leakage may be up to 30 % (Chen 2009). Despite the fact that NO_x, SO_2 and PM generate regional air quality issues they are a 'global–local' concern.

Life cycle assessment (LCA)

Increased public concern for environmental degradation has put pressure on the construction industry to move towards sustainable business practices. In response to this pressure, the construction industry has begun to reshape its *modus operandi*. This transformation is exemplified by the development of environment and energy certification systems such as those associated with the International Organization for Standardization (ISO) or the Leadership in Energy and Environmental Design (LEED) developed by the United States Green Building Council (Yeheyis et al. 2013).

The cornerstone of both ISO and LEED certification is life cycle assessment (LCA). LCA has become the principle assessment methodological tool for determining the complete environmental footprint of a product or process. The holistic approach considers all aspects of a product's development from cradle to grave. In the example of cement manufacturing an LCA may consider all the environment impacts starting from the initial geological survey to find a suitable limestone source to the packaging and transporting the finished product.

Cement and its primary end-use product concrete are widely used building materials with an average 1 tonne of concrete produced each year for every human being on earth. Given cement and concrete's extensive use, accurately determining the environmental impact of these materials is critical to understand their role in sustainable construction practices. Despite the emissions intense nature of cement LCA research may demonstrate the environmental performance of cement and concrete over its lifetime are higher than other building materials such as timber, steel, polymers, glass and bitumen.

Multi-criteria decision analysis (MCDA)

Industrial air emissions are a significant concern to human health and the environment. Development of standards and control mechanisms to reduce industrial emissions is important to protecting air quality. In order to develop sound environmental policy to air quality governments typically undertake some form of MCDA. MCDA attempts to combine social, environmental and economic assessment criteria into a single performance measure (Ascough et al. 2008; Yeheyis et al. 2013).

In light of the awareness around CO_2 emissions leakage, it is important to consider general emissions leakage and its role on the effectiveness of a policy or program to genuinely reduce emissions (Chen 2009; Barker et al. 2007). Unlike CO_2 emissions which add to global greenhouse gas concentrations, NO_x, SO_2 and PM emissions create local impacts. If creating environmental policy simply transfers regional air pollution to an unregulated jurisdiction, it defeats the purpose of developing said policy.

In a policy development scenario that considers regional pollutants, and applies MCDA to develop the appropriate standard, social (s), environmental (en) and economic (ec) criteria are considered:

$$\text{Standard for regional pollutant A} = \frac{1}{n}\sum_{i=1}^{n} g_i = \frac{g1(s) + g2(en) + g3(ec)}{n}. \quad (2)$$

However, if Eq. 2 fails to consider leakage effects there may be not net reduction in pollutant A because production may simply decrease locally and increase in an unregulated jurisdiction. In this instance a leakage factor (Lf) would need to be applied:

$$\text{Standard for regional pollutant A} = \frac{1}{n}\sum_{i=1}^{n} g_i = \frac{g1(s) + g2(en) + g3(ec)}{n}(\text{Lf}). \quad (3)$$

The value of the Lf would likely be proportional to productions costs. As an EITE industry cement manufacturing would require a greater Lf due to the high energy and labour costs. In a study of the environmental effects of exports and imports, Wang and Xie (2011) found that significant strain is being placed on China's environment because of the expansion of heavy industry designated for the export market. The lack of environmental regulation and cheap labour allows China to outcompete domestic producers in the developed world. In order to improve the quality of the environment in China, Wang and Xie (2011) suggest that environmental regulation needs to be strengthened and the scale of exports needs to be reduced.

Conclusions and recommendations

As with most industrial processes grey cement manufacturing generates air emissions. These emissions are produced throughout the life cycle of cement production from quarrying limestone to packaging and transporting the finished product. The largest contributors to air emissions from cement manufacturing are carbon dioxide (CO_2), oxides of nitrogen (NO_x), sulphur dioxide (SO_2) and particulate matter (PM) (WBCSD 2005).

Cement is one of the most widely used man-made substances on the planet, second only to water. It is estimated that each man, woman and child consume 350 kg of cement each year (WBCSD 2005). In 2008, global cement production was approximately 2.8 billion tonnes (WBCSD 2011). Despite the incredible need and consumption of cement for use in concrete to build housing and infrastructure, there is also an awareness of the environmental sustainability issues associated with the manufacturing process (WBCSD 2005).

In developed countries with strong environmental regulatory, activity consideration must be given offshoring production of industry. Countries such as China with significant air quality issues who make up for the lost production which no longer occurs locally, further impacts their already degraded air quality particularly in heavily industrialized areas. Apart from the well-document CO_2 leakage, air pollutant leakage is a critical consideration.

A direct comparison between Canada grey cement manufacturing performance and China's environmental performance is problematic. Firstly, the amount of production in Canada is far more manageable to monitor in comparison to China's massive inventory. Data inventory and monitoring requirement are poor. The CSI provides some analysis of China's cement production, however, these are new facilities and only cover 80 million tonnes of the $\approx$1.5 billion tonnes of cement produced in China.

Another opportunity for research is the potential to extend the environmental performance of cement to its primary role in concrete. Unlike other industrial processes where the output is a finished product, cement is in an intermediate step or a building block of concrete. Given cement is the emissions intense component of concrete, but, by composition only accounts for 7–11 % of concrete, it may be inappropriate to focus on only one component of the product.

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