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Information Sheet

Paper Title : Life Cycle Carbon Measurement of Locally Used Building Materials: Portland Cement and Ready-Mixed Concrete

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Construction activities account for much of the energy consumption and carbon emissions. According to WWF, the construction sector was the second largest contributor of the Hong Kong carbon emissions in 2007, and 85% of the carbon emissions from the sector was external in nature. The carbon footprint embodied in each building material varies considerably under different conditions. This study develops and illustrates a methodology framework to calculate embodied carbon footprints of building materials. The framework uses a "cradle-to-site" life cycle boundary which includes the processes of raw materials extraction, manufacturing and transport until the building material reaches the construction site. Data were collected from manufacturers in local and nearby regions. Portland cement and ready-mixed concrete were selected as examples in this study to demonstrate the calculation steps. The results indicate that for Portland cement, calcination is the largest contributor to the total GHG emission over the cement life cycle, followed by coal combustion. For ready-mixed concrete, the major contributor is the cement manufacturing. The methodology presented in this paper can be modified and extended to other building materials, thereby helping lower the carbon footprint of construction activities by providing a benchmark for the selection of green materials.

Keywords: *Building materials, Carbon footprint, Cradle-to-site, GHG emission, Portland cement, Ready-mixed concrete*

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Construction activities account for much of the energy consumption and carbon emissions. According to WWF, the construction sector was the second largest contributor of the Hong Kong carbon emissions in 2007, and 85% of the carbon emissions from the sector was external in nature. The carbon footprint embodied in each building material varies considerably under different conditions. This study develops and illustrates a methodology framework to calculate embodied carbon footprints of building materials. The framework uses a "cradle-to-site" life cycle boundary which includes the processes of raw materials extraction, manufacturing and transport until the building material reaches the construction site. Data were collected from manufacturers in local and nearby regions. Portland cement and ready-mixed concrete were selected as examples in this study to demonstrate the calculation steps. The results indicate that for Portland cement, calcination is the largest contributor to the total GHG emission over the cement life cycle, followed by coal combustion. For ready-mixed concrete, the major contributor is the cement manufacturing. The methodology presented in this paper can be modified and extended to other building materials, thereby helping lower the carbon footprint of construction activities by providing a benchmark for the selection of green materials.

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1. Introduction

In recent years, climate change and global warming issues have attracted increasing concern around the world. The Intergovernmental Panel on Climate Change (IPCC) states that anthropogenic greenhouse gas (GHG) emission is the major cause of global warming phenomenon (Pachauri and Reisinger, 2007). In response to demands for sustainable development, industry has a responsibility to lower energy consumption and GHG emission over the manufacturing life cycle. Within the industrial sector as a whole, construction activities account for much of the energy consumption and carbon emissions. According to the WWF's Hong Kong Ecological Footprint Report 2010 (Cornish *et al.*, 2011), in 2007 the construction sector contributed the second largest carbon footprint in Hong Kong, of which 85% was embodied in imported goods and services. In addition to direct emissions from the construction sector, this footprint includes emissions from all upstream material inputs to the construction activities.

This study aims to investigate the methods for calculating embodied carbon footprint of building materials. After reviewing various carbon footprint calculation methodologies for building materials, a modified methodology framework has been developed with consideration of regional factors, with the intention to develop a carbon inventory of the building materials commonly used in Hong Kong. The results of this study will help lower the carbon footprint of the construction industry in Hong Kong by providing a benchmark for the selection of green materials.

This paper describes our methodology framework and illustrates the steps to be taken in life cycle carbon measurement of building materials. Portland cement and ready-mixed concrete were selected as examples in this study in order to demonstrate the methodology framework, which can serve as a reference for the study of other types of building materials. Based on the concept of Life Cycle Assessment (LCA) and with reference to the ISO 14040 standard, the system boundary of this study is set as "cradle-to-site", which evaluates the life cycle environmental impact (i.e. carbon footprint) of building materials from the stages of raw materials extraction, product manufacture, and transport (ISO, 2006; Hammond and Jones, 2008).

2. Methodology Framework

The framework of this study is shown in Figure 1. To develop a region-specific inventory, the manufacturing processes for cement and concrete in local and nearby areas were studied, the GHG emission sources over the specified life cycle were identified, and the standard GHG emission calculation guidelines were reviewed. Based on the information obtained from the background study above, detailed system boundaries describing the manufacturing processes from "cradle-to-site" were determined for cement and concrete, respectively. Questionnaires specific to local and nearby manufacturers were then designed and distributed, with the aim to collect first-hand data. This data collection stage was the key to the whole study because the availability, quality and completeness of the data could influence the accuracy and reliability of the final results. In the data collection work, iterative review and revision of the questionnaires can be conducted in response to the feedbacks from industry. GHG emissions of the building materials were then calculated with reference to the relevant guidelines and standards. Finally, the results were analyzed, compared, and reported, which summarized the whole study.

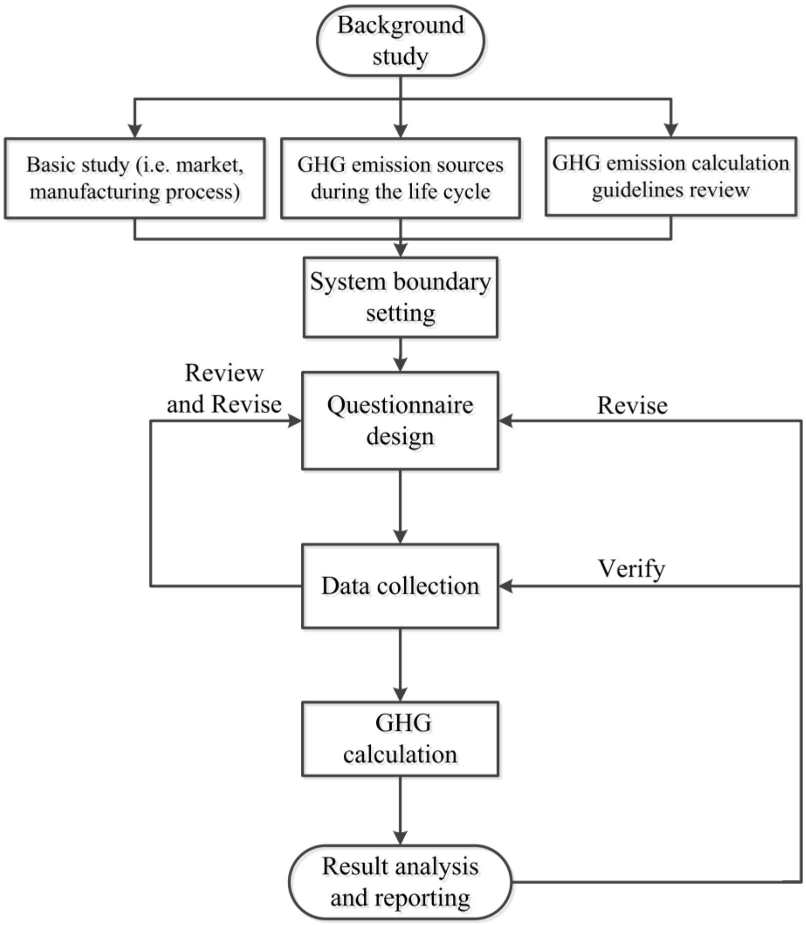

Figure 1. The methodology framework of this study

3. System Boundary

This section presents the "cradle-to-site" life cycle system boundaries for Portland cement and ready-mixed concrete in this study. As shown in Figure 2, the "cradle" of the system boundary for Portland cement refers to the extraction and quarrying of the four raw materials – limestone, clay, sand, and iron ore (Duggal, 1998). The raw materials are transported to manufacturing plants and then separately ground to fine powder and mixed. Calcination, a combustion process that consumes fuel is then performed. Due to the chemical reaction of the carbonates at a high temperature of 1400 ^{o}C to 1500 ^{o}C, CO_2 is directly emitted during calcination and clinker is produced (Duggal, 1998). During the production of clinker, limestone, which is mainly calcium carbonate ($CaCO_3$), is heated, or calcined, producing lime and CO_2 (Eggleston *et al.*, 2006). The chemical equation is given in Eq. 1.

$$CaCO_3 + heat \rightarrow CaO + CO_2 \quad (1)$$

In some factories, self-manufactured clinker cannot satisfy the demand for cement production, so clinker may be imported from other manufacturers. The GHG emissions from the production and transport of imported clinker are included in our system boundary for cement. After clinker preparation, gypsum is added for strengthening the performance of cement. Then the final grinding process produces the cement product. The last phase in the system boundary is the transport of the cement products. As shown in Figure 2, electricity and coal are the energy inputs during the cement manufacture process and account for GHG emissions.

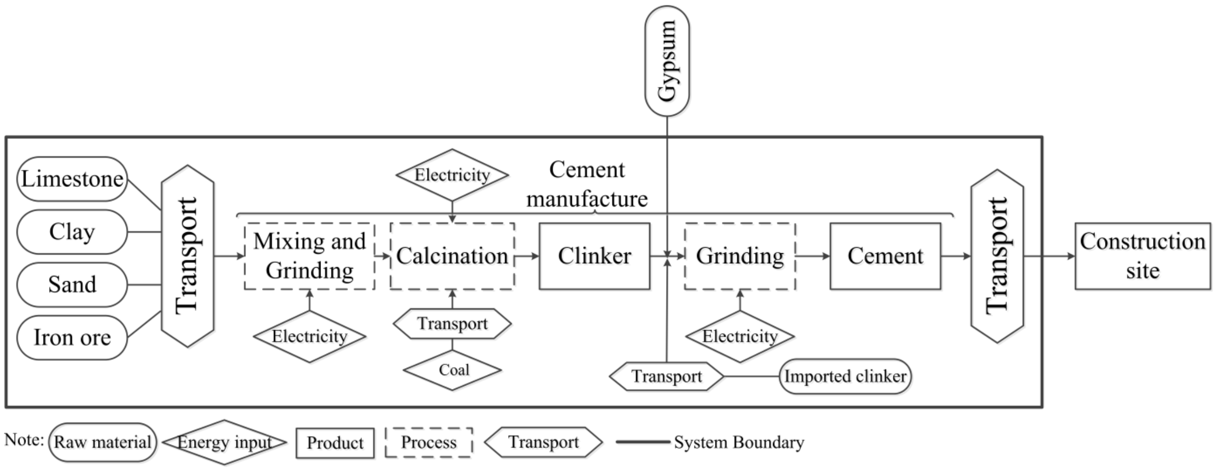

Figure 2. System boundary of Portland cement

All direct and indirect GHG emissions associated with each phase shown in Figure 2 are covered in this study. They are (1) the GHG emissions generated from each upstream material extraction process and production, (2) the GHG emissions from the transport of upstream materials, fuels, imported clinker and products, and (3) the GHG emissions during the cement manufacture process at factory (i.e. calcination, fuel combustion, electricity consumption, and imported clinker). However, the emission from the gypsum production is excluded since gypsum is a by-product of the desulfurization process in power plants.

Figure 3 shows the “cradle-to-site” life cycle system boundary of ready-mixed concrete. The raw materials include admixture, aggregates, cement, fly ash, and water (Richard, 2004).

After being transported to concrete batching plants, the raw materials are conveyed and loaded into silos for storage in the plants. The raw materials are then weighed in specific ratios for mixing. After mixing, the fresh ready-mixed concrete is transferred to construction sites using mixing trucks. Electricity is the energy input during the batching process.

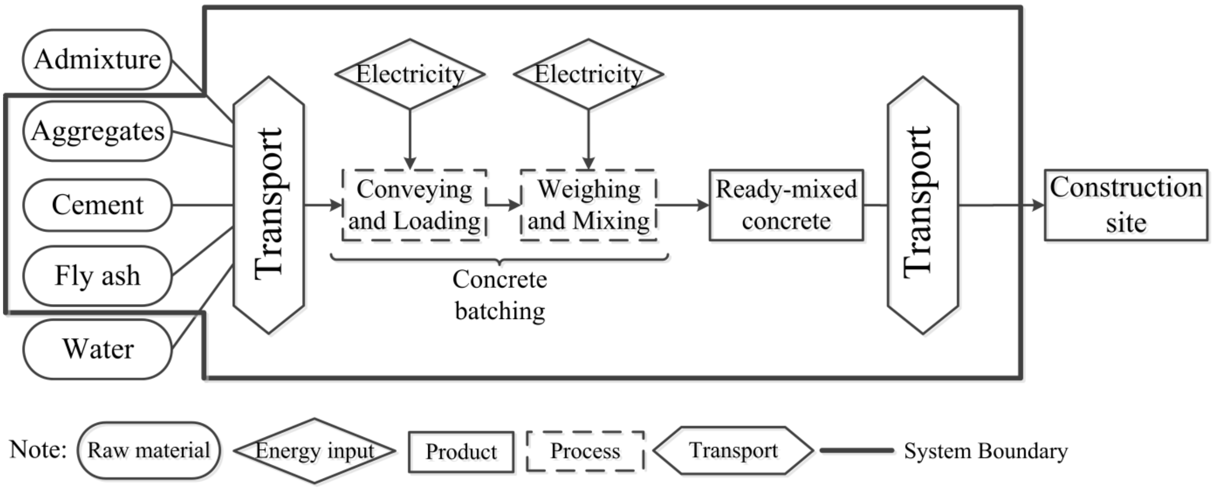

Figure 3. System boundary of ready-mixed concrete

The GHG emissions for concrete were calculated using the methods similar to those used for Portland cement. However, the "cradle" of the system boundary for concrete does not cover the extraction and production of admixture and water, because the admixture production and water use have an insignificant impact on the total GHG emission, according to Flower and Sanjayan (2007).

4. Questionnaire Design and Data Collection

Based on the information obtained from the background study and the literature review, a set of bilingual questionnaires (in English and Traditional Chinese) for cement and ready-mixed concrete manufacturers were developed. Following the system boundaries as described above, the main body of the questionnaires covers three major parts – (1) raw materials extraction and production, (2) consumption of fuels and electricity, and (3) transport of upstream materials, fuels and products.

Table 1. Basic information of the cement manufacturing factory example illustrated in this study (raw materials, fuel and electricity consumption, production, and transport)

Material	**Quantity (t/yr)**	**Source location**	**Transport type**
Limestone	416,000	Guangdong, China	Ship (inland water)
	624,000	South Japan	Ship (international marine)
Sand	130,000	Guangdong, China	Ship (inland water)
Clay	104,000	Guangdong, China	Ship (inland water)
Iron ore	26,000	South Japan	Ship (international marine)
Imported clinker	100,000	Vietnam	Ship (international marine)
Energy	**Quantity**	**Source location**	**Transport type**
Coal	237,900 (t/yr)	Indonesia	Ship (international marine)
Electricity	87 (kWh / t clinker)	NA	Local grid
	135 (kWh / t cement)	NA	Local grid
Product	**Quantity (t/yr)**	**Distance**	**Transport type**
Clinker	1,300,000	NA	NA
Cement	1,500,000	100 km	Barge
		100 km	Truck

To collect first-hand information about the locally used cement and concrete products, bilingual questionnaires were distributed to the manufacturers in Hong Kong and nearby regions that supply cement and concrete products to the Hong Kong market. For illustrative purposes, this paper shows the examples from one of the cement manufacturers and one of the ready-mixed concrete manufacturers. As requested, the manufacturers' names and the information sources are kept anonymous due to confidentiality. Some information and numbers are also hidden or slightly modified due to confidentiality. The modified raw material quantities, production data, and transport information for the cement and concrete illustrative examples are summarized in Table 1 and Table 2.

As shown in Table 1 and Table 2, compared to the concrete production example, the cement production example involves more materials imported from overseas regions such as Japan and Vietnam, resulting in longer transport distances. However, the concrete production example involves more types of transport means. Both transport distances and transport means types are considered in the GHG emission calculation.

Table 2. Basic information for the ready-mixed concrete batching plant illustrated in this study (raw materials, production and transport)

Raw material	Quantity (t/yr)	Source location	Transport type
Cement	530,000	Hong Kong/China	Cement tanker
Aggregate	2500,000	Hong Kong/China	Truck/Conveyor/Barge
Fly ash	99,000	Hong Kong	Tanker/Barge
Admixture	6,486	Hong Kong	Truck
Product	**Quantity (m^3/yr)**	**Diesel oil (L/yr)**	**Transport type**
Ready-mixed concrete	1,300,000	300000	Truck

5. Calculation of CO_2-e for Portland Cement

The results of our GHG emission calculation are expressed in terms of carbon dioxide equivalent (CO_2-e), which refers to the global warming potential (GWP) with respect to one unit of carbon dioxide. Expressing all GHG emissions in terms of CO_2-e allows the different greenhouse gases to be grouped together (British Columbia Ministry of Environment, 2013). Usually, the six greenhouse gases identified in Kyoto Protocol are considered when measuring GHG emissions in terms of CO_2-e. They are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro-fluorocarbons (HFCs), per-fluorocarbons (PFCs), and sulfur hexafluoride (SF_6). In this study, the three major ones (CO_2, CH_4 and N_2O) among the six were considered in calculation. The CO_2-e for a gas is derived by multiplying the weight of the gas by the corresponding GWP value, as expressed in Eq. 2 (USEPA, 2012).

$$\text{kg } CO_2\text{-e} = (\text{kg of a gas}) * (\text{GWP of the gas}) \quad (2)$$

IPCC has updated the GWP values for various greenhouse gases in 2007 and released the latest GWP values over a 100-year period in the IPCC Fourth Assessment Report: Climate Change 2007 (Foster *et al.*, 2007). This study uses the latest GWP values released by IPCC in 2007, as summarized in Table 3. According to 2006 IPCC Guidelines for National Greenhouse Gas Inventories, biogenic CO_2 emission is excluded for reporting in the Energy sector due to its neutral impact on the greenhouse effect (Eggleston *et al.*, 2006). However, according to the IPCC Fourth Assessment Report in 2007, biogenic CH_4 emission should be taken into account as sequestration of CO_2 with a GWP value of 22.5 (Frischknecht, 2012), as shown in Table 3.

Table 3. The GWP values of CO_2, CH_4 and N_2O

Gas type	GWP
Carbon dioxide (CO_2)	1
Methane from fossil source (CH_4 fossil)	25
Methane from biogenic source (CH_4 bio)	22.5
Nitrous oxide (N_2O)	298

The GHG emission calculation for Portland cement over its "cradle-to-site" life cycle consists of three parts: (1) extraction and production of upstream materials (raw materials and fuel), (2) cement manufacture at factory, and (3) transport of upstream materials and products.

(1) Upstream materials: For each upstream material, the emission factors in terms of different greenhouse gases are summarized in Table 4. To ensure that the results were region-specific, local data were selected as much as possible. For some data which could not be obtained from local sources, average values based on a global range from widely recognized inventories were adopted. The emission factors in terms of CO_2-e per kg of upstream material were calculated based on the GWP values shown in Table 3. As shown in the last column of Table 4, the CO_2-e value of coal is almost four times the CO_2 value, indicating the significant impact of CH_4 emission during coal mining.

Table 4. Emission factors of the upstream materials of Portland cement

Upstream material	kg CO_2/ kg material	kg CH_4 fossil/ kg material	kg CH_4 bio/ kg material	kg N_2O/ kg material	kg CO_2-e/ kg material
Limestone	4.83×10^{-3}	1.71×10^{-5}	5.59×10^{-9}	6.78×10^{-7}	5.45×10^{-3} [a]
	NA	NA	NA	NA	4.11×10^{-3} [b]
Sand	2.29×10^{-3}	2.66×10^{-6}	5.84×10^{-8}	0	2.36×10^{-3} [c]
Clay	2.84×10^{-3}	1.87×10^{-6}	5.21×10^{-9}	0	2.89×10^{-3} [d]
Iron ore	4.29×10^{-3}	4.06×10^{-6}	4.74×10^{-8}	0	4.39×10^{-3} [e]
Coal	2.56×10^{-2}	3.06×10^{-3}	4.68×10^{-7}	0	1.02×10^{-1} [f]

[a]*CLCD China, 2009;* [b]*JEMAI Japan, 2011;* [c]*Ecoinvent Swiss, 2010;* [d]*Ecoinvent Swiss, 2003;* [e]*Ecoinvent Global, 2007;* [f]*Ecoinvent Central Planned Asia and China, 2010.*

(2) Cement manufacture: As presented in Figure 2, GHG emissions are mainly from the chemical reaction in calcination and the associated energy inputs (coal combustion and electricity consumption). Table 5 shows the emission factors for each process of clinker and cement production. For calcination, the value was obtained based on the first-hand data provided by the factory with reference to the IPCC Guideline (Eggleston *et al*., 2006) and the Cement Sustainability Initiative (CSI) standard (CSI, 2012). According to the factory, the consumption of coal is 3.6×10^{-3} GJ/kg clinker. Emission factors for coal combustion were obtained from the Energy sector of the IPCC Guideline (Eggleston *et al*., 2006). Electricity consumption for clinker and cement are 87 kWh/tonne clinker and 135 kWh/tonne cement, respectively. The CO_2-e emission factor for electricity consumption refers to the local power plant which supplies power to the surveyed cement factory. In cement production, GHG emissions from imported clinker should be considered. According to the CSI Standard, the embodied carbon of imported clinker is 0.865 kg CO_2-e/kg imported clinker (CSI, 2012). Referring to the annual coal consumption amount and annual production quantities shown in Table 1, the GHG emissions during the cement manufacture process were calculated as 0.950 kg CO_2-e per kg of clinker produced and 0.917 kg CO_2-e per kg of cement produced.

Table 5. Emission factors for the Portland cement manufacture

Clinker	**kg CO_2/unit**	**kg CH_4/unit**	**kg N_2O/unit**	**kg CO_2-e /unit**
Calcination	0.551	0	0	0.551 kg/kg clinker
Coal	96 kg/GJ	0.01 kg/GJ	0.0015 kg/GJ	96.70 kg/GJ
Electricity	NA	NA	NA	0.59 kg/kWh
			CO_2-e/kg clinker	**0.950**
Cement	**kg CO_2/unit**	**kg CH_4/unit**	**kg N_2O/unit**	**kg CO_2-e /unit**
Calcination	0.478	0	0	0.478 kg/kg cement
Coal	96 kg/GJ	0.01 kg/GJ	0.0015 kg/GJ	96.70 kg/GJ
Electricity	NA	NA	NA	0.59 kg/kWh
Imported clinker	0.865	0	0	0.865 kg/kg imported clinker
			CO_2-e/kg cement	**0.917**

(3) Transport of upstream materials and products: As shown in Table 1, inland water shipping and international marine shipping are the two major transport types for raw materials in the illustrative example. The inland water shipping distance from Guangdong Province of mainland China to the factory was estimated, and the international marine shipping distances from Southern Japan, Vietnam, and Indonesia to the factory were extracted from a Japanese database which provides the travel distances among major ports in the world (JEMAI, 2012). The emission factor for inland water shipping in China was obtained from a Chinese LCI database (CLCD, 2010), while the emission factor for international marine shipping was obtained from World Resources Institute (WRI) (WRI, 2011). After unit conversion, Table 6 presents the transport emission factors in SI units.

The factory delivers cement products by barge and by truck with an estimated travel distance of 100 km. The emission factors of barge delivery were obtained from WRI (WRI, 2011). The emission factors of diesel oil truck delivery were obtained from the Hong Kong Environmental Protection Department (HKEPD) (HKEPD, 2010) and the Electrical and Mechanical Services Department (EMSD) (EMSD, 2012).

Table 6. Emission factors for the transport of upstream materials and cement products

Materials	**Distance (km)**	**kg CO_2/t.km**	**kg CH_4/t.km**	**kg N_2O/t.km**	**kg CO_2-e/t.km**
Limstone	250	1.25×10^{-2}	5.97×10^{-5}	6.16×10^{-7}	1.42×10^{-2} [b]
	3202 [a]	3.29×10^{-2}	2.81×10^{-6}	9.60×10^{-7}	3.33×10^{-2} [c]
Sand	250	1.25×10^{-2}	5.97×10^{-5}	6.16×10^{-7}	1.42×10^{-2} [b]
Clay	250	1.25×10^{-2}	5.97×10^{-5}	6.16×10^{-7}	1.42×10^{-2} [b]
Iron ore	3202 [a]	3.29×10^{-2}	2.81×10^{-6}	9.60×10^{-7}	3.33×10^{-2} [c]
Imported clinker	1764 [a]	3.29×10^{-2}	2.81×10^{-6}	9.60×10^{-7}	3.33×10^{-2} [c]
Coal	3555 [a]	3.29×10^{-2}	2.81×10^{-6}	9.60×10^{-7}	3.33×10^{-2} [c]
Product	**Distance (km)**	**kg CO2/t.km**	**kg CH4/t.km**	**kg N2O/t.km**	**kg CO2-e/t.km**
Cement	100 (Barge)	3.29×10^{-2}	2.81×10^{-6}	9.60×10^{-7}	3.33×10^{-2} [b]
	100 (Truck, diesel oil)	2.614 kg CO_2/L	1.45×10^{-4} kg CH_4/L	7.20×10^{-5} kg N_2O/L	2.64 kg CO_2-e/L [d]

[a]*JEMAI Japan, 2012;* [b]*CLCD, 2010;* [c]*WRI, 2011;* [d]*HKEPD, 2010.*

Table 7. Results comparison of CO_2-e for each part of Portland cement life cycle		
(1) Upstream material	**kg CO_2-e/kg clinker**	**kg CO_2-e/kg cement**
Limestone	3.718×10^{-3}	3.222×10^{-3}
Sand	2.358×10^{-4}	2.043×10^{-4}
Clay	2.309×10^{-4}	2.002×10^{-4}
Iron ore	8.785×10^{-5}	7.614×10^{-5}
Coal	1.868×10^{-2}	1.619×10^{-2}
Total CO_2-e in part (1)	**2.295×10^{-2}**	**1.989×10^{-2}**
(2) Cement manufacture	**kg CO_2-e/kg clinker**	**kg CO_2-e/kg cement**
Calcination	0.551	0.478
Coal combustion	0.348	0.302
Electricity consumption	0.051	0.080
Imported clinker	NA	0.058
Total CO_2-e in part (2)	**0.950**	**0.917**
(3) Transport	**kg CO_2-e/kg clinker**	**kg CO_2-e/kg cement**
Limestone	5.225×10^{-2}	4.528×10^{-2}
Sand	3.544×10^{-4}	3.071×10^{-4}
Clay	2.835×10^{-4}	2.457×10^{-4}
Iron ore	2.130×10^{-3}	1.846×10^{-3}
Imported clinker	4.474×10^{-3}	3.877×10^{-3}
Coal	2.163×10^{-2}	1.875×10^{-2}
Cement	3.770×10^{-3}	3.267×10^{-3}
Total CO_2-e in part (3)	**8.489×10^{-2}**	**7.357×10^{-2}**
Overall total CO_2-e emission	**1.058**	**1.010**

After determination of the emission factors for each part, the CO_2-e calculation per unit of clinker and cement could be calculated. By multiplying the quantities shown in Table 1 by the CO_2-e emission factors for each material or each process, the total CO_2-e emissions were calculated. The per unit GHG emissions were then calculated by dividing the total CO_2-e emissions by the clinker production quantity and the cement production quantity. Table 7 and Figure 4 present the final results and percentage distribution of each part, which clearly indicate that the cement manufacture part accounts for most of the GHG emissions over the "cradle-to-site" life cycle of Portland cement. The bar chart in Figure 4 shows that in the cement manufacture part, calcination is the largest contributor, followed by coal combustion.

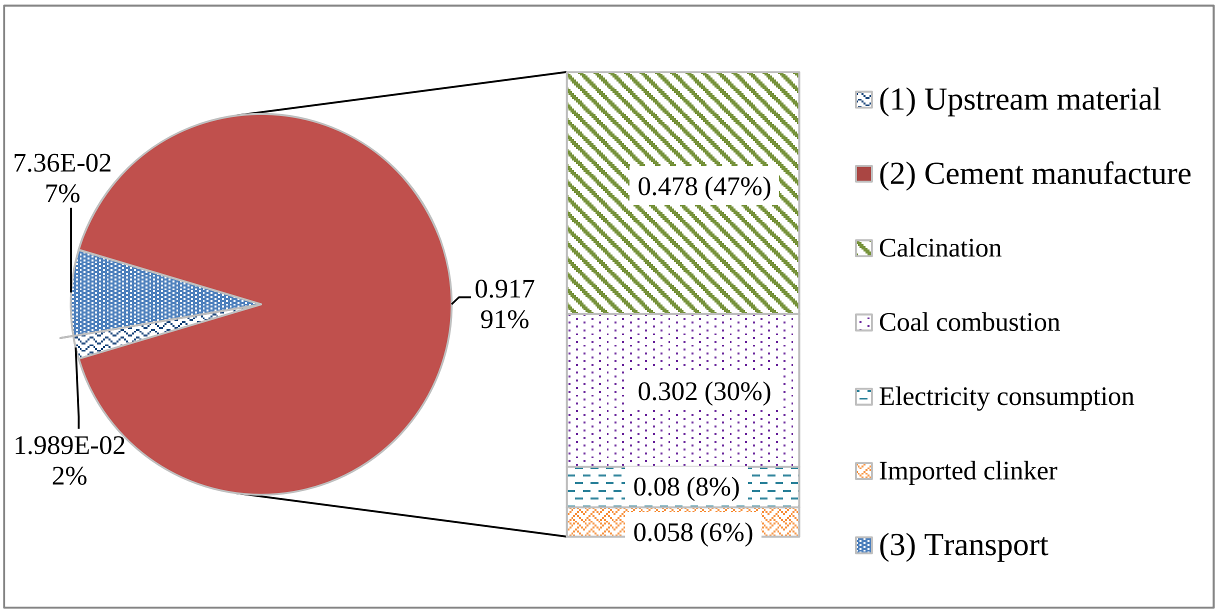

Figure 4. GHG emission distribution of each part for Portland cement (kg CO_2-e/kg cement)

6. Calculation of CO_2-e for Ready-Mixed Concrete

Similar to the study and calculation for Portland cement, this section presents the calculation of GHG emissions in terms of CO_2-e for ready-mixed concrete. The calculation consists of three parts: (1) extraction and production of upstream materials, (2) concrete batching at plants, and (3) transport of upstream materials and products.

(1) Upstream materials: As discussed above in Section 3, only three types of raw materials for ready-mixed concrete are included in the system boundary in this study. Emission factor for cement manufacture (0.917 kg CO_2-e/kg cement) referred to the previous calculation for Portland cement, as shown in Table 7. Emission factor of aggregate (3.07×10^{-3} kg CO_2-e/kg aggregate) was extracted from a report provided by the surveyed concrete batching plants. As for fly ash, since no local data was available, the emission factor (4.00×10^{-3} kg CO_2-e/kg fly ash) was obtained from a report published by Mineral Products Association in 2011 (Mineral Products Association, 2011).

(2) Concrete batching: The concrete batching process only consumes electricity as the energy input and is relatively simple compared to the cement manufacture process. According to the surveyed plants, electricity at the plants is provided by two suppliers. One supplier accounts for 98% of the electricity supply with a total annual consumption of 3,300,000 kWh, whereas the other supplier accounts for the remaining 2%. The emission factors of the first and the second electricity suppliers are 0.59 kg CO_2-e/kWh and 0.81 kg CO_2-e/kWh, respectively.

(3) Transport: Raw materials are transported to the concrete batching plants using road transport (trucks and tankers). The emission factor of concrete product road transport is the same as that of cement product road transport (HKEPD, 2010; EMSD, 2012), as shown in Table 6. Cement and fly ash are transported to the plants close to the raw material suppliers by pipeline and transported to other plants by truck. The emission factor of pipeline transport is 0.005 kg CO_2-e/t.km, as suggested by McKinnon and Piecyk (2010). Aggregates are transported by conveyor for the batching plants near the quarry site. In this case, GHG emissions due to conveyor transport are included in the electricity consumption. Barge delivery is needed when the supplier or batching plant is located on an island. The emission factor of barge delivery is 0.033 kg CO_2-e/t.km.

Applying the emission factors determined in the above three parts, the total GHG emission was calculated. To obtain the CO_2-e value per unit weight of concrete, the density of the ready-mixed concrete was assumed as 2400 kg/m^3 concrete (Richard, 2004). Table 8 summarizes the final calculation results for each part in terms of kg CO_2-e/m^3 concrete and kg CO_2-e/kg concrete. As indicated in Table 8, the part of upstream material extraction and processing contributes the majority of the total GHG emission, because cement as raw material has a rather high embodied carbon value.

Table 8. Results comparison of CO_2-e for each part of ready-mixed concrete life cycle		
(1)Upstream material	**kg CO_2-e/m^3 concrete**	**kg CO_2-e/kg concrete**
Cement	373.86	0.1558
Aggregate	5.90	0.0025
Fly ash	0.30	0.0001
Total CO_2-e in part (1)	**380.06**	**0.1584**
(2) Concrete batching	**kg CO_2-e/m^3 concrete**	**kg CO_2-e/kg concrete**
Electricity supplier 1	1.47	6.1156×10^{-4} [a]
Electricity supplier 2	0.04	1.7135×10^{-5} [a]
Total CO_2-e in part (2)	**1.51**	**0.0006**
(3) Transport	**kg CO_2-e/m^3 concrete**	**kg CO_2-e/kg concrete**
Raw materials transport	1.42	0.0006
Products transport	0.61	0.0002
Total CO_2-e in part (3)	**2.03**	**0.0008**
Total CO_2-e emission	**383.60**	**0.1598**

[a] *Figures may not add up to total due to rounding off.*

The results of this study were compared with the values provided by Inventory of Carbon & Energy (ICE), a widely used UK-based carbon inventory database of building materials developed by University of Bath (Hammond and Jones, 2008). The system boundary of ICE is “cradle-to-gate”. In other words, our “cradle-to-site” system boundary in this study has a broader coverage than ICE and includes the GHG emissions from transport of products which ICE excludes. In order to make a fair comparison, the results of this study were converted to “cradle-to-gate” values by deducting the emissions of product transport from the previous “cradle-to-site” calculation. Table 9 shows the details of the comparison. The ICE value for cement was selected from the type “CEM I Portland cement” in ICE, which is the type of cement studied in this paper. For concrete, the average cement content of the concrete studied in this paper is 407.7 kg/m^3 concrete, calculated based on the annual cement consumption quantity and annual concrete production volume. Therefore, the ICE value for concrete was selected from the specific type of concrete in ICE that contains 400 kg cement in one cubic meter of concrete (“400 kg CEM I/m^3 concrete”). As shown in Table 9, the result for cement presented in this study is larger than the ICE value. In addition, the result for concrete presented in this study is smaller than the ICE value, probably because the concrete plants surveyed in this study add fly ash as cement replacement in the batching process, reducing the amount of cement necessary for each unit volume of concrete. However, the concrete type "400 kg CEM I/m^3 concrete" in ICE does not include the addition of fly ash.

Table 9. Results comparison of CO_2-e between ICE and this study

Database	**kg CO_2-e/kg cement**	**kg CO_2 –e/m^3 concrete**	**System boundary**
ICE	0.950	0.1810	Cradle-to-gate
This study	1.007	0.1596	Cradle-to-gate
This study	1.010	0.1598	Cradle-to-site

7. Conclusion and Future Work

This paper presents and illustrates the methodology framework developed for measuring the life cycle carbon emissions of locally used building materials in Hong Kong. A "cradle-to-site" life cycle system boundary was used in this study. To illustrate the steps of GHG emission calculation, Portland cement and ready-mixed concrete were selected as examples in this paper. The results show that calcination and coal combustion are the major sources of GHG emissions for cement over its "cradle-to-site" life cycle, whereas the high embodied carbon emission in cement manufacture is the largest contributor to GHG emission for ready-mixed concrete over its "cradle-to-site" life cycle The results were then compared with the values provided in the ICE database developed by University of Bath.

As the values of embodied carbon are region-specific, this study aims to collect first-hand data in Hong Kong and nearby regions, wherever possible, for accuracy and reliability of the final results. However, when the information from the manufacturers was limited, the second-hand information from existing databases or literature would be used. In addition, some assumptions were made for the manufacturing and transport calculation due to the limited information. The methodology framework presented in this paper can be applied to building materials other than cement and concrete. In the near future, the scope of this study will be extended to more building materials and a building materials carbon inventory database will be developed for the Hong Kong market. Such a database could help build a low carbon built environment in Hong Kong by providing a benchmark for selection of green construction materials and a basis for prediction of carbon emission in building infrastructures.

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Figure captions

Figure 1. The methodology framework of this study

Figure 2. System boundary of Portland cement

Figure 3. System boundary of ready-mixed concrete

Figure 4. GHG emission distribution of each part for Portland cement (kg CO_2-e/kg cement)

Table captions

Table 1. Basic information of the cement manufacturing factory example illustrated in this study (raw materials, fuel and electricity consumption, production, and transport)

Table 2. Basic information of the ready-mixed concrete batching plant illustrated in this study (raw materials, production and transport)

Table 3. The GWP values of CO_2, CH_4 and N_2O

Table 4. Emission factors of the upstream materials of Portland cement

Table 5. Emission factors for the Portland cement manufacture

Table 6. Emission factors for the transport of upstream materials and cement products

Table 7. Results comparison of CO_2-e for each part of Portland cement life cycle

Table 8. Results comparison of CO_2-e for each part of ready-mixed concrete life cycle

Table 9. Results comparison of CO_2-e between ICE and this study