START2SEE
LIFE CYCLE ASSESSMENTS

LCA OF GEOPOLYMER CONCRETE (E-CRETE)

FINAL REPORT

AURORA CONSTRUCTION MATERIALS (ACM)
14 DECEMBER 2012
S1207

Project Details

Project Title
ACM – LCA of Geopolymer Concrete (E-Crete)

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Report version	Author(s)	Date
Final report V1.0	**Rob Rouwette**	**14 December 2012**

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Executive summary

Concrete is the most widely used construction material in the world. The basic constituents of standard concrete are cement, water, coarse and fine aggregates. The major contributor of greenhouse emissions in the manufacture of concrete is Portland cement. Portland cement contributes 5-8% of global man made carbon emissions[1]. The cause of high emissions during Portland cement manufacture has been attributed to: (i) calcination of limestone, which leads to formation and release of carbon dioxide (CO_2); and (ii) high energy consumption during production.

This life cycle assessment presents an estimate of the reduction in greenhouse gas emissions (GHG) that can be achieved through the replacement of Portland cement based concrete with E-Crete, a geopolymer based concrete product manufactured by Aurora Construction Materials (ACM).

ACM manufactured E-Crete uses a geopolymer binder, up to 100% reclaimed stone (coarse aggregates), up to 15% manufactured sand (fine aggregates) and up to 100% captured or reclaimed water (mix water), resulting in a significant reduction in life cycle emissions compared to traditional concretes. Furthermore, E-Crete is capable of meeting Green Star Concrete Credit performance criteria and can contribute towards earning points needed for Green Star certification.

[1] WWF-Lafarge Conservation Partnership, A Blueprint for a Climate Friendly Cement Industry: How to Turn Around the Trend of Cement Related Emissions, 2008 http://assets.panda.org/downloads/cement_blueprint_climate_fullenglrep_lr.pdf

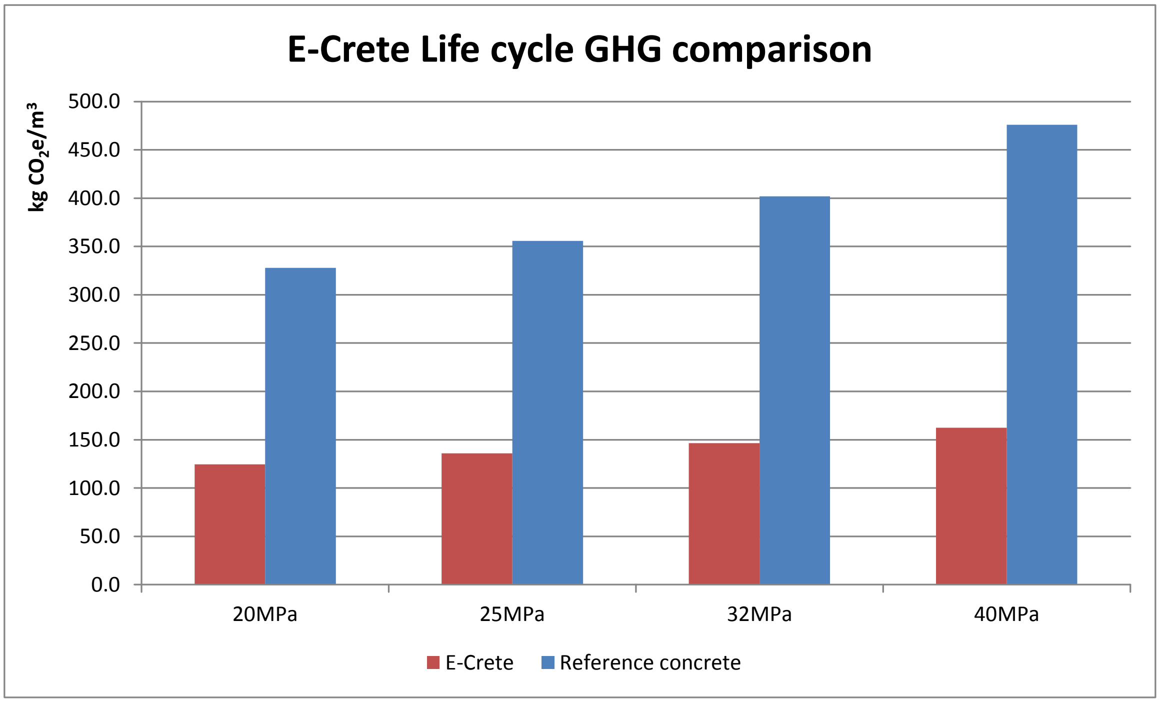

Figure 1. Life Cycle comparison of E-Crete and Reference Portland cement based concrete

Across its full life cycle, E-Crete delivers savings in GHG (CO_2e) emissions of 62-66% compared to traditional concrete (Figure 1). This is primarily driven by the savings achieved through the use of geopolymer E-Crete binder which, based on the binder materials only, achieves savings of 81-82% compared to the reference Portland cement binder.

1 Project Brief

Aurora Construction Materials (ACM) has commissioned start2see to prepare an environmental Life Cycle Assessment (LCA) report for "E-Crete" and to compare the environmental impacts against a standard, reference Portland cement concrete (standard concrete).

This report summarises the LCA methodology, key data and results.

2 E-Crete

E-Crete is a geopolymer concrete that is not based on Ordinary Portland Cement; instead it uses low CO_2 materials (typically fly ash and blast furnace slag) reacted with an alkaline activator to form a hardened binder. The strength and durability in a geopolymer binder mainly comes from the reaction of aluminium and silicon, instead of calcium and silicon in the case of Portland cement.

Figure 2. E-Crete Placement (Port Melbourne)

Figure 3. E-Crete Footpath (Calder Freeway Interchange)

3 LCA Scope and Methodology

3.1 Objective

The objective of this LCA is to quantify the environmental impacts of E-Crete and to compare these against a standard Portland cement concrete.

3.2 Functional unit

E-Crete is available in various strength classes. Therefore, multiple permutations have been defined for the functional unit:

> *1 m^3 of [strength class (in MPa)] concrete, which complies with standard AS1379 for use in general concrete applications with a minimum service life of 50 years.*

The strength classes considered include 20 MPa, 25MPa, 32MPa and 40MPa.

E-Crete has similar transport requirements to standard concrete. For the purpose of this study the products are considered to be applied within a 25 km radius of ACM's plant in Melbourne. ACM intends to establish multiple additional facilities for E-Crete around Melbourne. The validity of the LCA results for other locations in the greater Melbourne area is tested through a sensitivity analysis (section 5.1.6).

3.3 System boundaries

The life cycle of concrete for general concrete paving and non-structural use such as footpaths, pavements, flooring, and kerb and guttering is provided in Figure 4. The system boundaries indicate which parts of the life cycle have been included in the LCA.

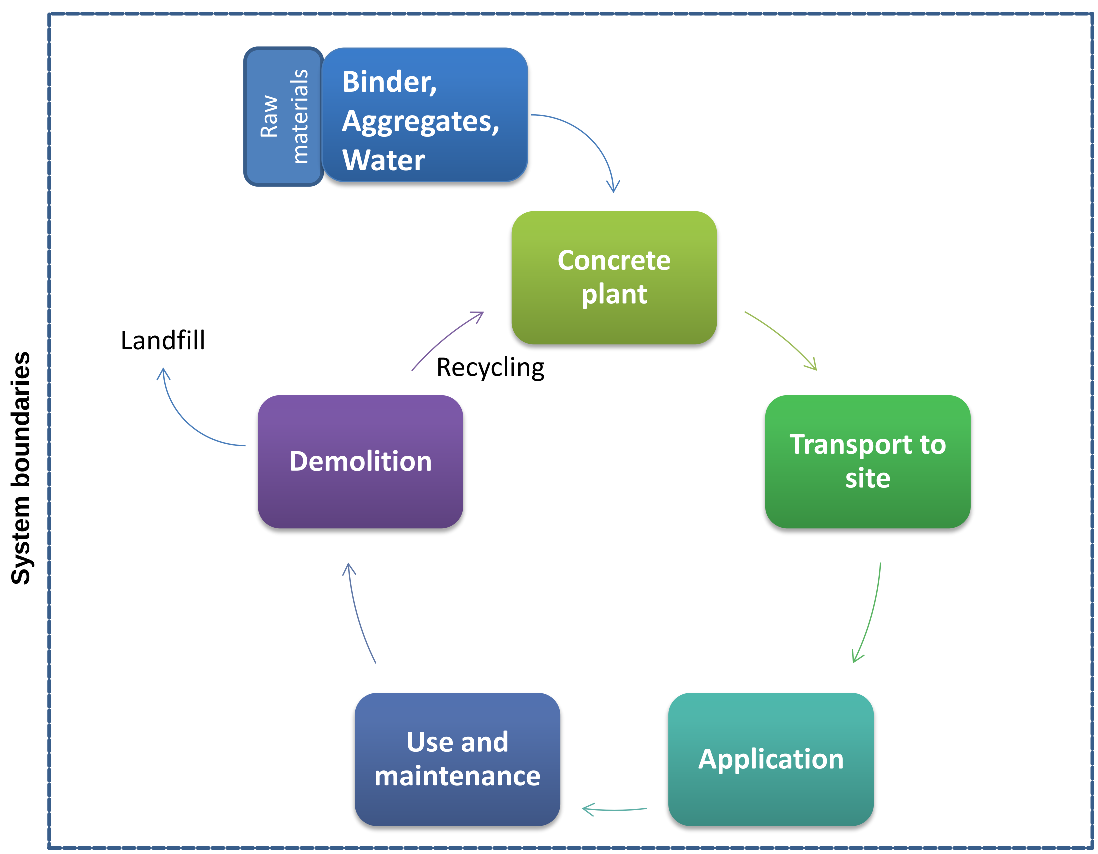

Figure 4. System boundaries for the LCA of E-Crete and standard concrete

3.4 Product system

This life cycle assessment study investigates the life cycles of various types of concrete used for general concrete paving and non-structural applications. This section details the relevant aspects in the life cycle of E-Crete and a standard reference concrete.

The life cycle stages considered for all concrete types are identical and cover:

- Raw material extraction
- Production of wet concrete
- Transport to customer site
- Placing, compacting, finishing and curing
- Use in application of hardened concrete
- Maintenance of hardened concrete
- Demolition of concrete
- Collection and disposal or recycling of the used material.

Transport between all life cycle stages is included. A detailed description for each life cycle stage is given hereafter.

3.4.1 Raw material extraction and production

The key raw materials for E-Crete and standard concrete as well as their production processes are described in the following table.

Table 1. Raw material extraction and production processes

Raw material	Production process
Cement (GP)	Portland cement clinker is ground with gypsum and potentially mineral addition (e.g. raw limestone) in ball mills to make a general purpose (GP) cement. The cement is transported as a fine powder to Melbourne where it is stored in silos until transport by truck to concrete batch plant.
Fly-ash	By-product from (black) coal fired power stations, captured by electrostatic precipitators and stored in silos until transport by truck to concrete batch plant.
Ground Granulated Blast Furnace Slag (GGBFS)	Granulated Blast Furnace Slag (GBFS) is a by-product of iron and steel-making, made by quenching molten iron/steel slag from a blast furnace in water or steam, to produce glassy, granular sand. GBFS is allowed to drain and is transported with 10-12% moisture. GBFS is ground into a fine powder (GGBFS) with a vertical roller mill and stored in silos until transport by truck to concrete batch plant.
Activator	Alkali and alkali earth containing salts, minerals and/or glasses; made through a range of extraction and chemical processes; stored until transport by truck to concrete batch plant.
Fine aggregates (sand)	Sand is scraped from a river bed; screened; washed; scrubbed; graded; stored onsite and allowed to drain until transport by truck to concrete batch plant.
Coarse aggregates (stone)	Quarried stone is blasted from a rock face; crushed; screened; graded; stored onsite until transport by truck to concrete batch plant
Manufactured Sand	Crusher fines from aggregate production; crushed using equipment onsite and used at the concrete batch plant.
Reclaimed Coarse Aggregate (Basalt)	Selected surface rock is excavated from surrounding subdivisions; transported by truck to ACM; stockpiled; crushed using equipment onsite and used at the concrete batch plant.
Water (Potable)	Water of sufficient quality for consumption and use by humans as distributed by water authorities.
Water (Captured or Reclaimed)	Rainwater captured on either the concrete supplier’s manufacturing site, or another site, or recycled/recovered from a previous use such as black water or grey water from any locations.

3.4.2 E-Crete/Concrete production

Concrete is produced by mixing accurately weighed raw materials in a batch plant. ACM provided energy use data for its concrete batch plant in Epping, Victoria. Energy use was considered equivalent for all concrete grades. The relevant mix designs for both E-Crete and standard Portland cement concrete (reference concrete) are provided in the following tables.

Table 2. E-Crete composition

Components (kg / m^3)	E-Crete 20MPa	E-Crete 25MPa	E-Crete 32MPa	E-Crete 40MPa
Portland cement	-	-	-	-
E-Crete Binder (Fly ash, GGBFS and Activator)	260-280	300-320	340-360	420-440
(Calculated on a solids basis, activator for all mix designs is less than 50kg/m^3)				
Fine aggregates	750-800	750-800	700-750	650-700
Coarse aggregates	-	-	-	-
Manufactured sand	100-150	100-150	100-150	100-150
Reclaimed coarse aggr.	900-1000	900-1000	900-1000	900-1000
Water (potable)	-	-	-	-
Water (captured or reclaimed)	170-190	170-190	170-190	170-190
TOTAL	**2250-2300**	**2250-2300**	**2250-2300**	**2250-2300**

Note that the exact mix design is used for the calculation of greenhouse gas emissions in the LCA, but for confidentiality reasons only a basic overview is provided above.

Table 3. Reference concrete composition (GBCA 2012)

Components (kg / m^3)	Reference concrete 20MPa	Reference concrete 25MPa	Reference concrete 32MPa	Reference concrete 40MPa
Portland cement	280	310	360	440
GGBFS	-	-	-	-
Fly ash	-	-	-	-
Fine aggregates	755	740	690	610
Coarse aggregates	1045	1030	1030	1030
Manufactured sand	-	-	-	-
Reclaimed coarse aggr.	-	-	-	-
Water (potable)	170-190	170-190	170-190	170-190
Water (captured or reclaimed)	-	-	-	-
TOTAL	**2260**	**2260**	**2260**	**2260**

Concrete admixtures (accelerators, water reducers, air entrainers etc.) are not considered in this LCA due to the wide range of types and typically small amounts used compared to other components. This exclusion may have a (minor) impact on the relative results of the LCA.

3.4.3 Transport to site

E-Crete and concrete mixes are assumed to be transported to site by concrete agitator trucks (with rotating barrel). The products are not typically transported long distances due to the economics of transporting heavy materials and the initiation of the chemical reactions after mixing. In this study, a conservative average one-way distance of 15 km has been assumed based on ACM plant data.

3.4.4 Application

The application of concrete consists of a number of distinct processes:

- Placing (through pouring or pumping).
- Compacting and vibrating.
- Finishing (screeding, floating or trowelling by hand or machine).
- Curing (e.g. with curing compounds, water or sheeting).

The application of E-Crete occurs in a similar manner to the application of standard Portland cement concrete, with both requiring good practice application practices to ensure the best quality outcomes.

For the purpose of this comparison, any use of formwork and reinforcement steel is excluded. This exclusion may have a (minor) impact on the relative results of the LCA.

3.4.5 Use and Maintenance

Use of E-Crete or standard concrete in general concrete paving and non-structural applications does not require any structural maintenance or replacement under normal circumstances (assuming good practice application). Therefore, no greenhouse gas emissions are attributed to the use of concrete during the service life.

3.4.6 Demolition

Concrete paving or non-structural applications at the end of their useful life are typically either left as a foundation layer for a new paving or demolished to make way for a new product. Demolition by excavator is assumed here.

3.4.7 End-of-life

At the end of its functional life a concrete product can be recycled (through crushing) into "recycled concrete aggregates". In Australia, based on (Commonwealth of Australia 2010) & (Hyder Consulting 2009) the end-of-life scenario for general concrete paving and non-structural applications has been defined as 75% recycling, with the remaining 25% disposed of in landfill.

Explained: Uptake of CO_2 by Portland cement concrete
The uptake of CO_2 by concrete (a process called carbonation) has not been considered within this LCA.
1) During the functional life of concrete carbonation is often an undesired process, as it is associated with the corrosion of steel reinforcement.(WHD Microanalysis Consultants, 2012a)
The carbonation depth of concrete structures is limited (about 20 mm from the surface after 50 years (Flower & Sanjayan 2007)) and depends on the density and permeability of the concrete. More importantly, most of the CaO in cement forms part of the hardened concrete and is thus not available for carbonation.
2) At the end-of-life stage, concrete is either crushed for recycling or larger sections end up in landfill sites. Crushing will increase the surface area of the concrete and thereby increase the potential for CO_2 uptake. In an ideal scenario all the free CaO (less than 2% according to WHD Microanalysis Consultants 2012b) reacts with CO_2 from the air, which means not more than 2% of the calcination emissions are re-absorbed. In a more realistic scenario the re-absorption of CO_2 by concrete during its lifetime is more likely to be in the order of 1% or less, and is not considered in the calculations of this LCA.

3.5 Environmental indicators

The key environmental indicator considered is climate change. This indicator is measured by the total amount of greenhouse gas emissions, expressed in carbon dioxide equivalents (kg CO_2e). It is commonly referred to as the "carbon footprint" of a product.

Where possible, the Global Warming Potentials (GWP) are taken from the Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment Report (AR4) (Forster et al. 2007), using a 100 year time horizon. These are the latest GWP's currently available.

Furthermore, four environmental criteria based upon the (GBCA 2012) revised concrete credit are presented:

- Reduction of Portland cement content in concrete, by replacing it with supplementary cementitious materials.
- The percentage of captured or reclaimed water used for the mix water for all concrete.
- The percentage of crushed slag aggregate or another alternative material (measured by mass) that is used as coarse aggregate in the concrete, provided that use of such materials does not increase the use of Portland cement by over five kilograms per cubic meter of concrete.
- The percentage of manufactured sand or other alternative materials (measured by mass) that is used as fine aggregate (sand) in the concrete, provided that use of such materials does not increase the use of Portland cement by over five kilograms per cubic meter of concrete.

3.6 Life Cycle Inventory (LCI) data

Data has been sourced from ACM and a range of publicly available literature. The key data and assumptions are discussed in this section.

3.6.1 Raw material extraction and production

Extraction and production of raw materials results in greenhouse gas emissions from the use of energy as well as from process emissions. The following table details the emission factors used in this study, including their sources. These emission factors cover (cradle-to-gate) production. Transport of raw materials to site (i.e. Epping concrete plant for ACM) is not included in these factors and has been calculated separately.

Table 4. Emission factors for raw materials

Raw material	Emission factor (t CO_2e/t)	Source
Cement (GP)	0.904	Cement is considered to contain 90% clinker, 5% gypsum and 5% mineral addition (raw limestone) - Clinker emissions from (Commonwealth of Australia 2011) - Gypsum emissions modelled in SimaPro[2] - Raw limestone emissions from SimaPro[3] - Cement milling from (Worrell et al. 2001)

[2] Process: "*Gypsum, at mine/AU*". Source: CRC for Waste Management and Pollution Control
[3] Process: "*Limestone, milled, loose, at plant/SA-AU*". Source: Kellenberger D, Althaus H-J, Jungbluth N, Künniger T 2007, 'Life Cycle Inventories of Building Products', Final report ecoinvent data v2.0. Volume: 7. Swiss Centre for LCI, Empa - TSL. Dübendorf, CH

Ground Granulated Blast Furnace Slag (GGBFS)	0.113	(Heidrich, Hinczak and Ryan 2005)
Fly-ash	0.027	(ADAA 2012)
Activator	1.070	Activator production modelled in SimaPro[4]
Fine aggregates (sand)	0.003	Sand energy use modelled in SimaPro[5]
Coarse aggregates	0.0052	The crushing process is assumed to have the same emissions as production of (crushed) reclaimed coarse aggregate. Although drilling and blasting are not accounted for, this has a negligible impact.
Manufactured sand (crusher fines)	0.0052	Manufactured sand is a by-product of aggregate production. It is assumed to have the same emission factor as crushed reclaimed coarse aggregate on a mass basis
Reclaimed coarse aggregate (Basalt)	0.0052	ACM crushing plant data, cross-referenced with (McRobert J 2010)
Water (potable)	$7x10^{-4}$	(Kenway 2008)
Water (captured or reclaimed)	$7x10^{-5}$	Assumed to have 10% of the impacts of reticulated water, due to significantly reduced pumping and treatment requirements.

Transport of raw materials to the concrete plant has been included based upon actual transport modes and distances relevant to ACM. Reference GP cement is assumed to be transported from the nearest cement works facility to Melbourne. For quarried coarse aggregates (not typically used by ACM) transport of 20 km by truck is assumed.

3.6.2 E-Crete/Concrete production

ACM provided approximate annual energy use (electricity and diesel) and production volume data for their concrete batch plant. The average emissions data per m^3 of concrete was considered representative for all mix designs as the processes are similar.

[4] Process: "*Sodium silicate, furnace process, pieces, at plant/adjusted to AU U*". Source: Zah R, Hischier R 2007, 'Life Cycle Inventories of Detergents', Final report ecoinvent data v2.0. Volume: 12. Swiss Centre for LCI, Empa - TSL. Dübendorf, CH
[5] Process: "*Sand, at mine/AU*". Source: ACI minerals P/L 1997

Table 5. Emission factors for concrete production

Process	Emission factor ($t\ CO_2e/m^3$)	Source
E-Crete production	0.0018	ACM (observed to be equivalent to standard concrete production)
Reference concrete production	0.0018	ACM (average for concrete batch plant)

3.6.3 Transport to site

In this study, an average one-way distance of 15 km has been assumed. The emission factor for a concrete truck was modelled in SimaPro[6].

3.6.4 Application

Accurate quantification of the energy required for the application activities (placing, compacting, finishing, curing) of concrete is challenging to accurately model due to the variety in application processes, large range of end uses and the relatively small quantities of energy required. A conservative figure of emissions generated during application processes was estimated at 0.009 t CO_2e/m^3 (Flower & Sanjayan 2007). An estimate of 0.005 t CO_2e/m^3 for the application of E-Crete and standard concrete has been used in this study reflecting use in general concrete paving and non-structural purposes.

E-Crete and standard concrete are assumed to be delivered with an additional 2% of material to account for wastage during the construction process. Wet E-Crete/concrete waste is most often returned to the concrete plant and used in concrete production.

3.6.5 Use and Maintenance

The use and maintenance of the concrete's life cycle is typically fairly small or non-existent (if no maintenance is required) and is considered equivalent for E-Crete and standard concrete. The LCA assumes normal operation of the products during the service life and calamities that would lead to unscheduled maintenance requirements are not foreseen. Cleaning of the concrete product is excluded from the life cycle as this is considered user dependent.

[6] Process: "*Concrete truck/AU*". Source: Apelbaum Consulting Group 1997, 'Australian Transport Facts'

3.6.6 Demolition

Energy use data for demolition processes are not readily available. Therefore, to estimate climate change impacts it has been assumed that an excavator capable of demolishing 5 m^3 of general concrete paving and non-structural applications per hour is used. The estimated diesel consumption[7] for the excavator is 7.6 l/hr. There is no difference in demolition requirements for E-Crete and standard concrete.

3.6.7 End-of-life

At the end of the functional life, both E-Crete and standard concrete can be recycled (through crushing) into "recycled concrete aggregates". The end-of-life scenario for general concrete paving and non-structural applications has been defined as 75% recycling, with the remaining 25% disposed of in landfill. (Commonwealth of Australia 2010) & (Hyder Consulting 2009)

Concrete waste is assumed to be transported by truck over 30 km to a recycling site (crusher) or 50 km to a landfill site. Energy required for crushing concrete waste is considered outside the system boundaries of this LCA. In effect this energy is attributed to the life cycle that uses recycled concrete aggregates. This is a simplification of the life cycle model to avoid allocation that has negligible impact on the LCA. This practice does not alter the comparison as the impact on E-Crete and standard concrete is equal.

Concrete is an inert material that does not decompose in a landfill site. Management of landfill sites (use of front-end loaders, landfill compactors, etc.) requires diesel, and hence some of the associated emissions are attributed to concrete sent to landfill.

Table 6. Emission factors for concrete end-of-life processes

Process	Emission factor (t CO_2e/m^3)	Source
Concrete recycling	0.0133	Transport emissions modelled in SimaPro[8]
Concrete disposal in landfill	0.0279	Transport emissions[8] and landfill management[9] modelled in SimaPro

[7] www.deere.com/en_US/docs/construction/non_current_products/excavators/DKAX80C0212.pdf
[8] Process "*Rigid truck, per unit freight moved/AU*". Source: Apelbaum Consulting Group 1997, 'Australian Transport Facts'
[9] Process "*Disposal, concrete, 5% water, to inert material landfill/CH*". Source: Doka G 2009, 'Life Cycle Inventories of Waste Treatment Services', Final report ecoinvent data v2.1. Volume: 13. Swiss Centre for LCI, Empa - TSL. Dübendorf, CH.

4 Life Cycle Assessment results

4.1 Climate change impacts

The reduction in greenhouse gas emissions for E-Crete compared to standard concrete are primarily attributed to savings achieved through the use of a geopolymer binder. The E-Crete binder (activator, fly ash & GGBFS) has ca. 80% lower embodied greenhouse gas intensity than an equivalent amount of ordinary Portland cement binder used in reference concrete of a similar strength.

As E-Crete and standard concrete are similar in non-binder materials used and behaviour after production, there is some dilution of the benefits when measured over the full life cycle. The greenhouse gas emissions during the life cycle of E-Crete are approximately 62%-66% lower than emissions from the reference concrete, as detailed in Table 7 and Figure 5.

A detailed evaluation of E-Crete's emissions is provided in section 5.

Table 7. Life cycle greenhouse gas emissions of E-Crete and the GBCA reference concrete

Strength class	E-Crete ($kg\ CO_2e/m^3$)	GBCA Reference concrete ($kg\ CO_2e/m^3$)	Reduction
20 MPa	124.6	327.9	62%
25 MPa	136.0	355.8	62%
32 MPa	146.5	402.0	64%
40 MPa	162.3	476.0	66%

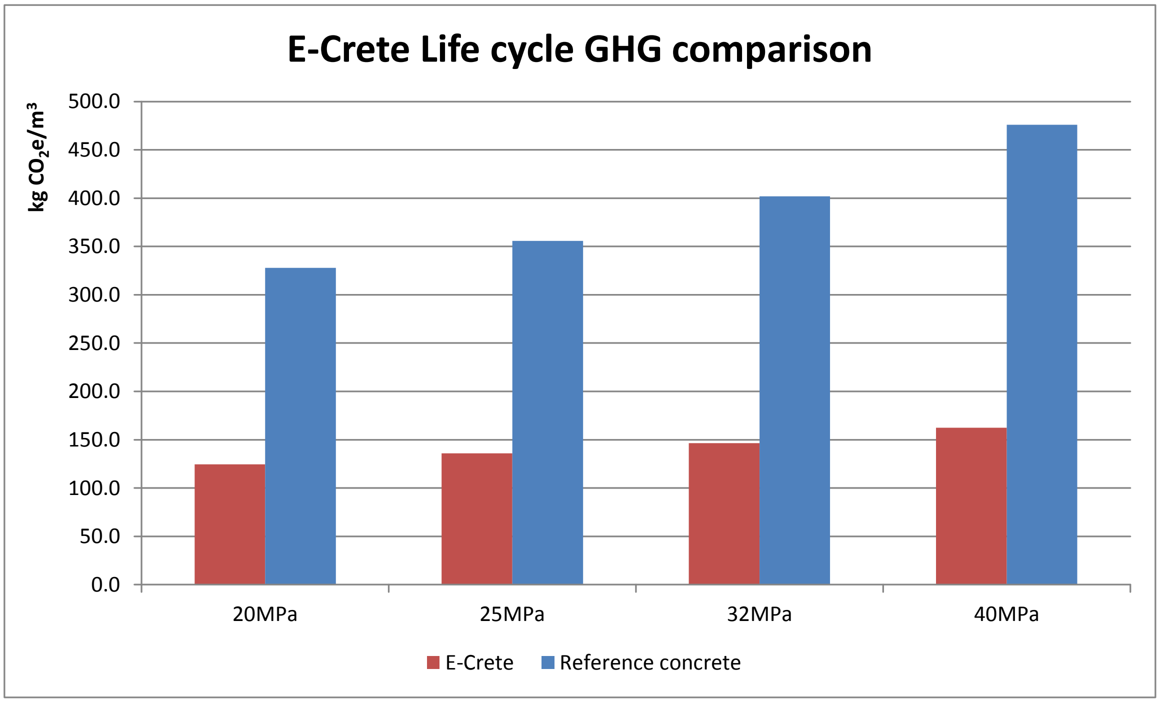

Figure 5. Life cycle greenhouse gas emissions of E-Crete and the GBCA reference concrete

4.2 Reduction of Portland cement content

E-Crete is a geopolymer concrete that is not based on Portland cement and can therefore assist in achieving an overall Portland cement reduction across all concrete used in a Green Star project.

GBCA revised concrete credit: Portland cement credit criteria

Up to two points are available where the Portland cement content in all concrete used in the project has been reduced by replacing it with supplementary cementitious materials.

- One point is awarded where the Portland cement content is reduced by 30%, measured by mass across all concrete used in the project compared to the reference case; or
- Two points are awarded where the Portland cement content is reduced by 40%, measured by mass across all concrete used in the project compared to the reference case.

4.3 Captured or reclaimed water used for mix water

Up to 100% of E-Crete's mix water is captured or reclaimed. In combination with the use of recycled/reclaimed/alternative aggregates, E-Crete can thus assist in achieving one point for the aggregates and water credit in a Green Star project.

GBCA revised concrete credit: aggregates and water credit criteria
One point is available where the mix water for all concrete used in the project contains at least 50% captured or reclaimed water (measured across all concrete mixes in the project), and one of the following criteria is met:

- At least 40% of coarse aggregate in the concrete is crushed slag aggregate or another alternative materials (measured by mass across all concrete mixes in the project), provided that use of such materials does not increase the use of Portland cement by over five kilograms per cubic meter of concrete;
- At least 25% of fine aggregate (sand) inputs in the concrete are manufactured sand or other alternative materials (measured by mass across all concrete mixes in the project), provided that use of such materials does not increase the use of Portland cement by over five kilograms per cubic meter of concrete.

4.4 Coarse aggregate replacement

ACM manufactured E-Crete uses coarse aggregates which are sourced from reclaimed basalt and are eligible to be counted as alternative coarse aggregates under the GBCA's credit. In combination with the use of reclaimed water, E-Crete can thus assist in achieving one point for the aggregates and water credit in a Green Star project. (Please note that compliance with the requirements is always measured across all concrete used in a project.)

4.5 Fine aggregate replacement

Aurora Construction Materials produces manufactured sand as a by-product from its crushing plant. Part of E-Crete's fine aggregates are sourced from this basalt based manufactured sand, which is eligible to be counted as reclaimed fine aggregate under the GBCA's credit. In combination with the use of reclaimed water, E-Crete can thus assist in achieving one point for the aggregates and water credit in a Green Star project. (Please note that compliance with the requirements is always measured across all concrete used in a project.)

Table 8. Fine aggregate (sand) replacement

	20 MPa	25 MPa	32 MPa	40 MPa
Total fine aggregates (kg/m^3)	850-950	850-950	800-900	750-850
Manufactured sand (kg/m^3)	100-150	100-150	100-150	100-150
% reclaimed material in fine aggregates	<15%	<15%	<15%	<15%

As is evident from the table above, the replacement of (natural) sand inputs remains below the GBCA's requirement of minimum 25% replacement of fine aggregates. E-Crete will therefore depend on the composition of other concrete used in a project if a credit point is intended to be claimed based upon use of reclaimed water AND fine aggregate replacement. Of course, proponents can always attempt to achieve a credit point for use of reclaimed water AND coarse aggregate replacement instead.

5 Evaluation

A breakdown of how various life cycle stages contribute to the greenhouse gas emissions of E-Crete is provided in Figure 6. Production of E-Crete from its raw materials is responsible for 69% to 76% of the carbon footprint. This percentage increases with the compressive strength of E-Crete.

The end-of-life (mainly transport to recycling and landfill) contributes about 14% to 18% of the overall greenhouse gas emissions. Other life cycle stages (transport to site, application, demolition) are less pertinent and have a combined contribution of ca. 10 to 13%.

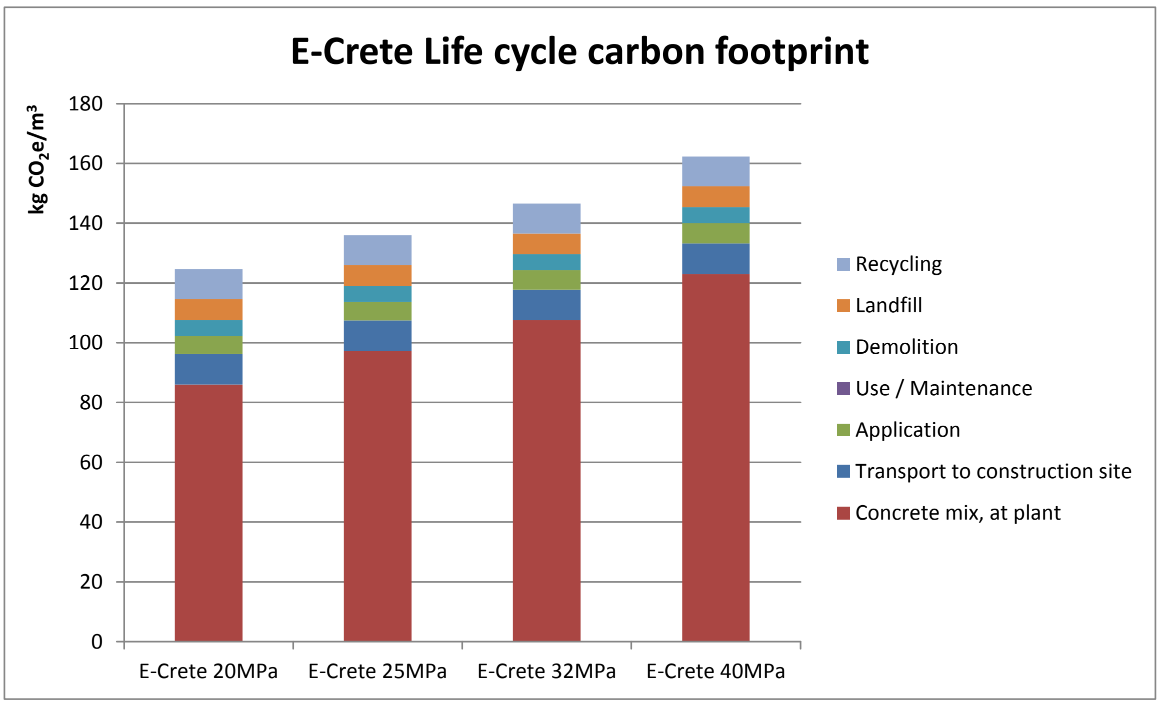

Figure 6. Breakdown of E-Crete life cycle carbon footprint

For the Portland cement reference concrete 87-90% of the carbon footprint is associated with the concrete mix at plant (Figure 7). For all mix designs, both E-Crete and standard concrete, the absolute values for transport to site through to demolition, landfill and recycling are very similar, contributing between 39 and 46 kg CO_2e/m^3.

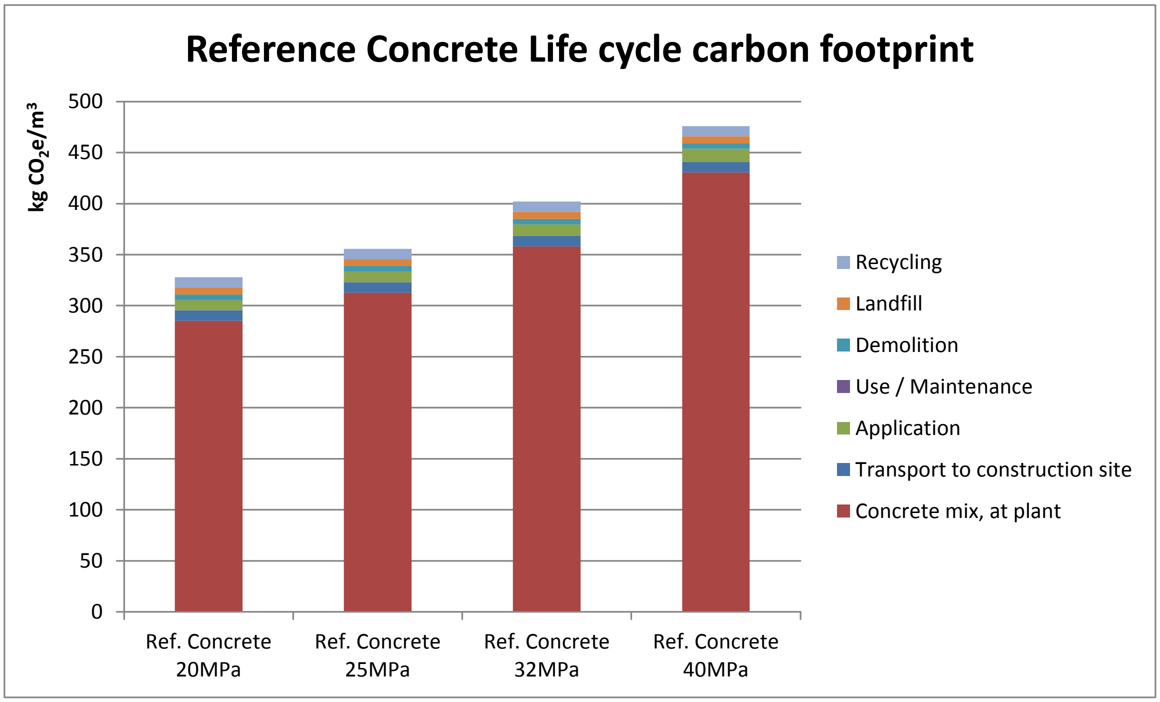

Figure 7. Breakdown of reference concrete life cycle carbon footprint

5.1 Sensitivity analyses

Sensitivity analyses have been performed to study the impact of key choices and assumptions within the LCA. The following sections discusses the impact on the greenhouse gas emission results of activator, cement, virgin aggregates and location of the concrete plant from transport of raw materials and transport to site perspective.

5.1.1 Activator

The emission intensity of the activator used in E-Crete is calculated to be 1.07 t CO_2e/t. This figure is viewed as a conservative estimate and is higher than what is estimated by one of ACM's main activator suppliers.

Published literature data sources for activator components of geopolymer binders (Duxson et al. 2007, Flower & Sanjayan 2007, Fawer, Concannon & Rieber 1999, McGuire et al. 2011, McLellan et al. 2011, Turner & Collins 2012) show significant variations in emission intensity. The primary activators each have several different methods and pathways of production, which can have a significant impact on the emissions and energy profile of the material. This LCA takes in to account:

- Source of each alkaline component (geographical location, manufacturing method, energy source for processing stages)
- The production and processing of raw materials and inputs
- Transport of alkaline components to ACM.

The low estimate and high estimate scenario for E-Crete, assumes emission intensity of the activator (excluding transport) of 500 kg CO_2e/t and 2000 kg CO_2e/t respectively. The impact of these variations on the E-Crete life cycle carbon footprint is shown in Figure 8 and demonstrates that even in a high activator scenario, E-Crete still generates under half the emissions of the reference concrete.

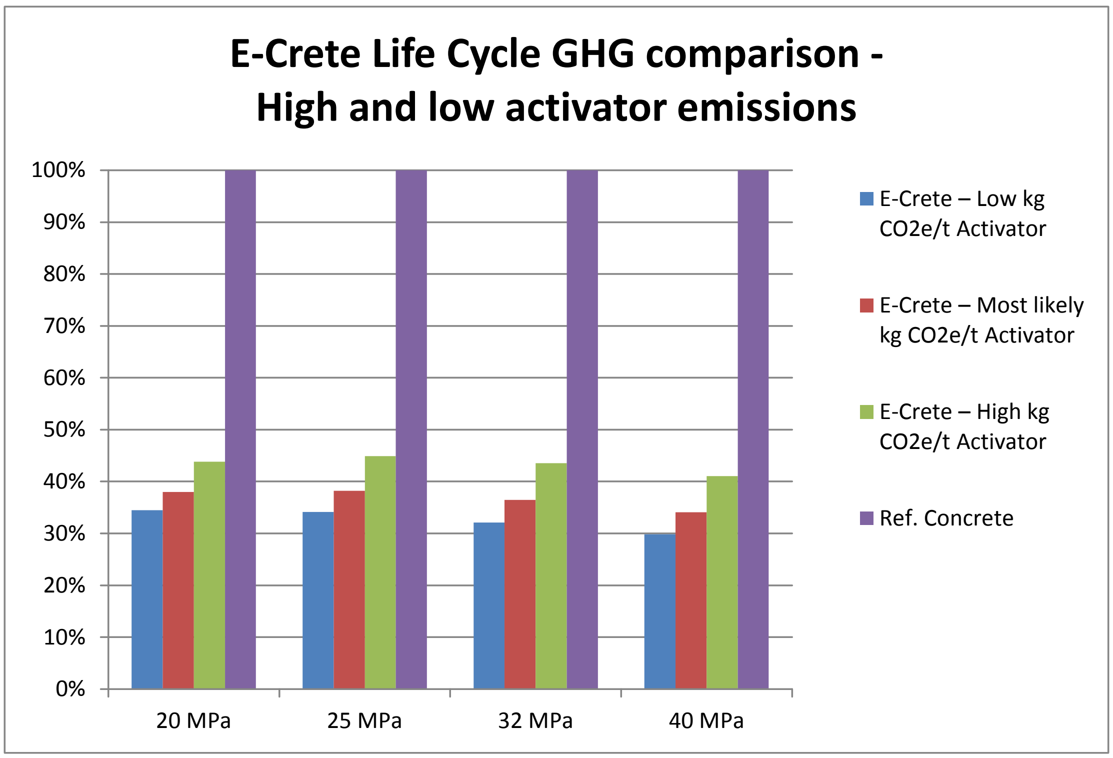

Figure 8. Sensitivity analysis: Effect of emission intensity of activators on E-Crete emissions

The reason for E-Crete's performance is the low emission intensity of the geopolymer binder compared to ordinary Portland cement. In a binder to binder comparison, based on the binder materials needed for 1 m^3 of concrete only, a similar analysis demonstrates that E-Crete binder's carbon footprint is more than 80% lower than Portland cement's carbon footprint (72-87% reduction across the high/low emissions intensity scenarios for the activator; see Figure 9).

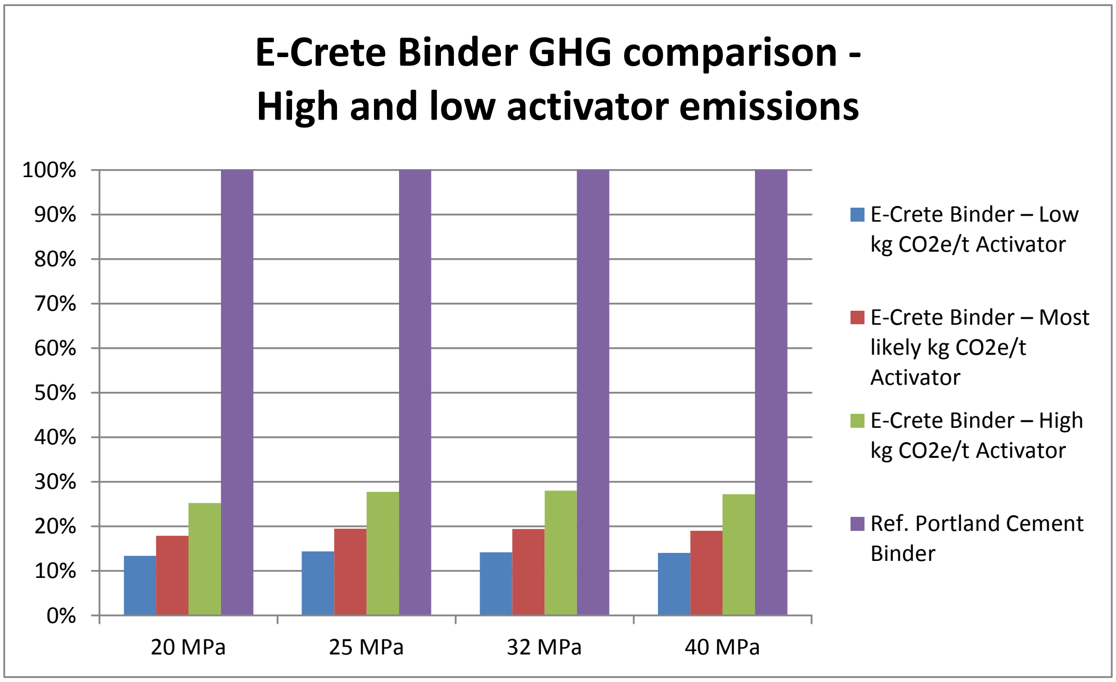

Figure 9. Sensitivity analysis: Effect of emission intensity of activators on E-Crete binder emissions

5.1.2 Cement

Appendix A shows how the emission intensity of cement is determined. The emissions intensity of Portland cement used in this study is quite even-handed, and by no means reflects the high end of what can be expected for cradle-to-gate emissions factors for cement. To study the impact of the cement composition and the cement grinding efficiency on the results, a sensitivity analysis of high and low estimates is conducted (see Table 9 and Table 10).

Table 9. Emission intensity of cement – high estimate

Material	Contribution (t / t)	Emission factor	Contribution to cement Emissions intensity
Clinker	0.950 x	0.957 t CO_2e/t	0.909 t CO_2e/t
Gypsum	0.050 x	0.183 t CO_2e/t	0.009 t CO_2e/t
Mineral addition	0.000 x	0.036 t CO_2e/t	0.000 t CO_2e/t
Cement grinding	1.000 x	0.043 t CO_2e/t	0.043 t CO_2e/t
Portland Cement			**0.962 t CO_2e/t**

Table 10. Emission intensity of cement – low estimate

Material	Contribution (t / t)	Emission factor	Contribution to cement Emissions intensity
Clinker	0.875 x	0.957 t CO_2e/t	0.837 t CO_2e/t
Gypsum	0.050 x	0.183 t CO_2e/t	0.009 t CO_2e/t
Mineral addition	0.075 x	0.036 t CO_2e/t	0.003 t CO_2e/t
Cement grinding	1.000 x	0.022 t CO_2e/t	0.022 t CO_2e/t
Portland Cement			**0.871 t CO_2e/t**

The impact of these variations on the reference concrete life cycle carbon footprint is less than 5% (see Table 11). As such, it does not substantially impact on the overall conclusions of this LCA.

Table 11. Sensitivity analysis: Effect of cement emission intensity

Strength class	Concrete – low scenario (kg CO_2e/m^3)	Concrete – best estimate (kg CO_2e/m^3)	Concrete – high scenario (kg CO_2e/m^3)
20 MPa	318.6	327.9	344.4
25 MPa	345.5	355.8	374.1
32 MPa	390.1	402.0	423.3
40 MPa	461.4	476.0	501.9

5.1.3 Maximum binder impact

When considering the range of emission intensities for activator and cement, the total spread in footprint reductions is found when combining the low activator / high cement scenarios (greatest reduction) as well as the high activator / low cement scenarios (smallest reduction).

Table 12. Sensitivity analysis: Maximum effect of binder emission intensity

Strength class	Low activator / High cement % Emission reduction E-Crete	Best estimate % Emission reduction E-Crete	High activator / Low cement % Emission reduction E-Crete
20 MPa	67%	62%	55%
25 MPa	68%	62%	54%
32 MPa	69%	64%	55%
40 MPa	72%	66%	58%

Table 12 shows that when considering the worst case scenario for E-Crete activator emission intensity and best case scenario for Portland cement emission intensity, E-Crete still reduces life cycle GHG emissions by 54-58%. In a more optimistic scenario (low activator emission intensity and higher Portland cement emission intensity) E-Crete reduces life cycle GHG emissions by 67-72%.

5.1.4 Virgin Aggregates

In the scenario that E-Crete is manufactured with virgin aggregate and potable water only, the emission intensity across all strength grades of E-Crete changes by 1-2% (Figure 10) due to higher transport requirements.

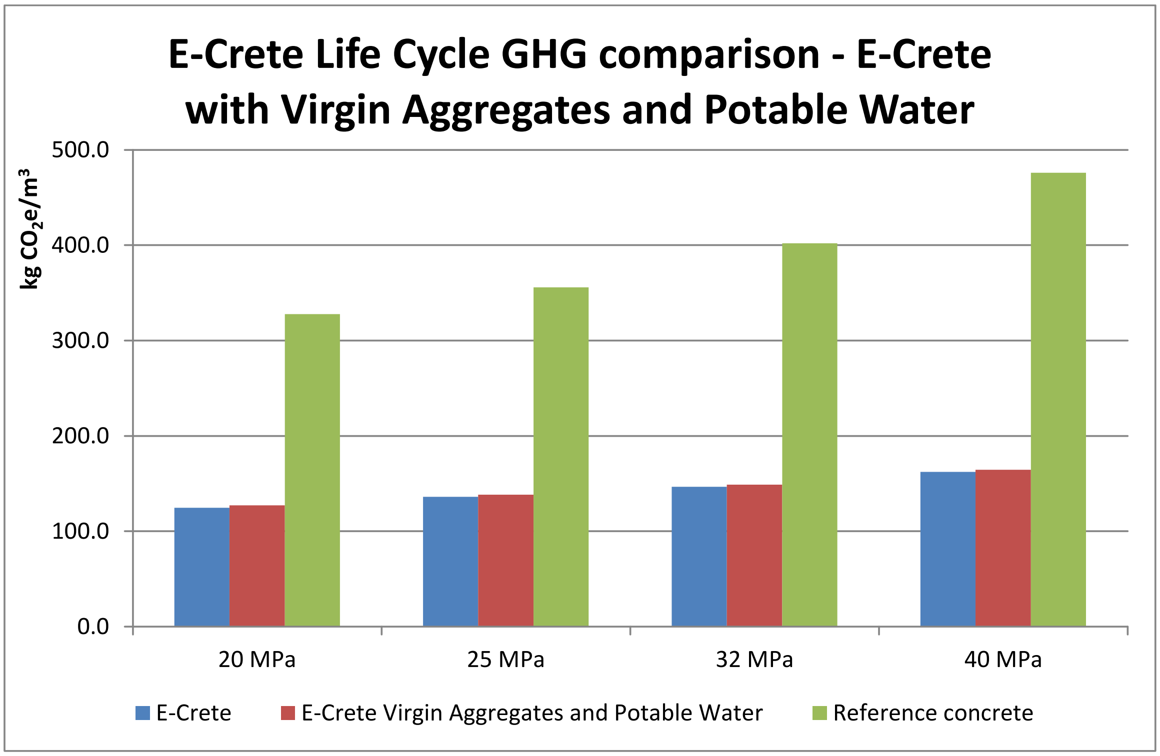

Figure 10. Sensitivity analysis: Effect of virgin aggregates and potable water on E-Crete emissions

5.1.5 Transport of Raw Materials

ACM has indicated that E-Crete is likely to be manufactured in multiple locations across Melbourne. The validity of the LCA results for other locations in the greater Melbourne region is tested through this sensitivity analysis. When considering the contribution of the various raw materials to transport emissions, three materials are responsible for over 85% of transport emissions: fine aggregates, GGBFS and fly-ash.

The potential impact of manufacturing E-Crete at different locations is:

- Fly ash: These are transported by truck from NSW (ca. 1020 km). If the trucking distance to another concrete plant's location in greater Melbourne would increase to 1100 km, it would affect the life cycle impacts of E-Crete by less than 0.5%.
- GGBFS: Slags are imported and transported to plant by truck from Port Melbourne (ca. 40 km). Increasing the trucking distance to 100 km would affect the life cycle impacts of E-Crete by less than 1%.
- Fine aggregates: These are transported by truck; an increase in transport distance of 50km would add 3-5% to the life cycle impacts of E-Crete.

Transport of reclaimed coarse aggregates and manufactured sand currently has only a minor contribution to the life cycle carbon footprint of E-Crete because of the use of locally available materials. If the same material from northern Melbourne would be transported across the metropolitan area (e.g. increase the transport distance to 80 km) the life cycle impacts of E-Crete would increase by 6-8%. ACM is most likely to use local sourced aggregate for any new site locations. In which case, E-Crete's carbon footprint does not necessarily increase (and may even decrease).

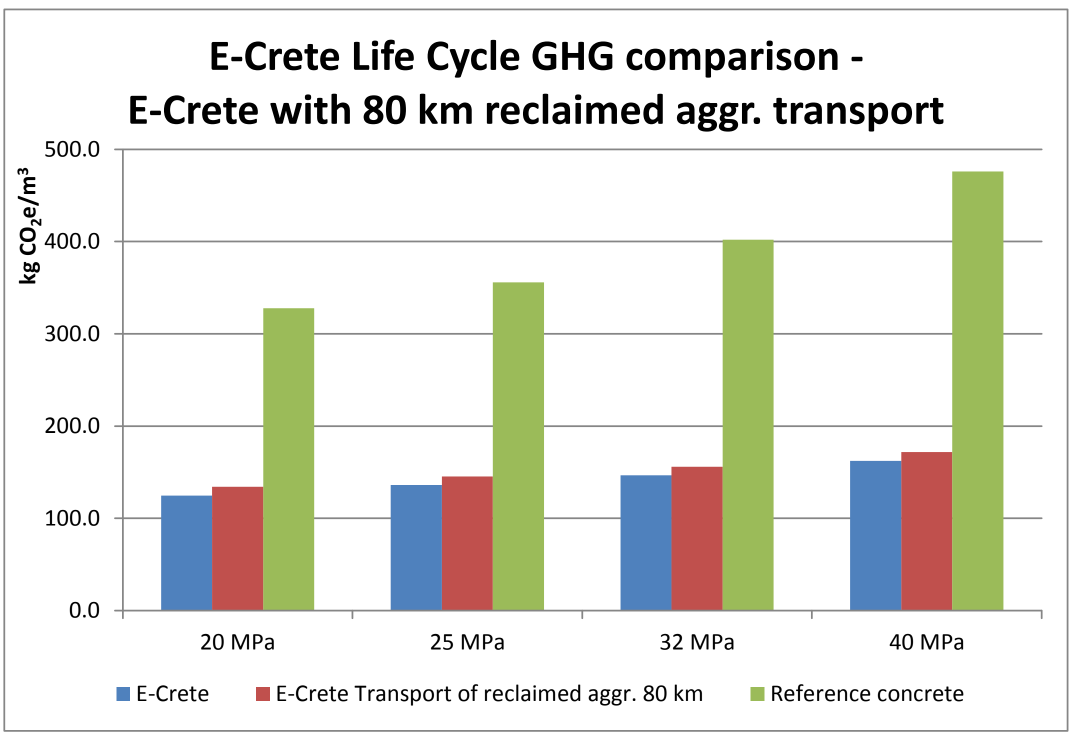

Figure 11. Sensitivity analysis: Effect of transport distance for reclaimed aggregates to concrete plant on E-Crete emissions

5.1.6 Transport Distance to Site

Due to a limited number of supply locations, for specific projects E-Crete may be transported in a concrete truck for distances greater than industry standard. Figure 12 shows the increased emissions for E-Crete transported 50 km compared to a 15 km one way journey for typical E-Crete and standard concrete supply. When extending the haul distance to 50 km, E-Crete's life cycle emissions increase by 15-19%.

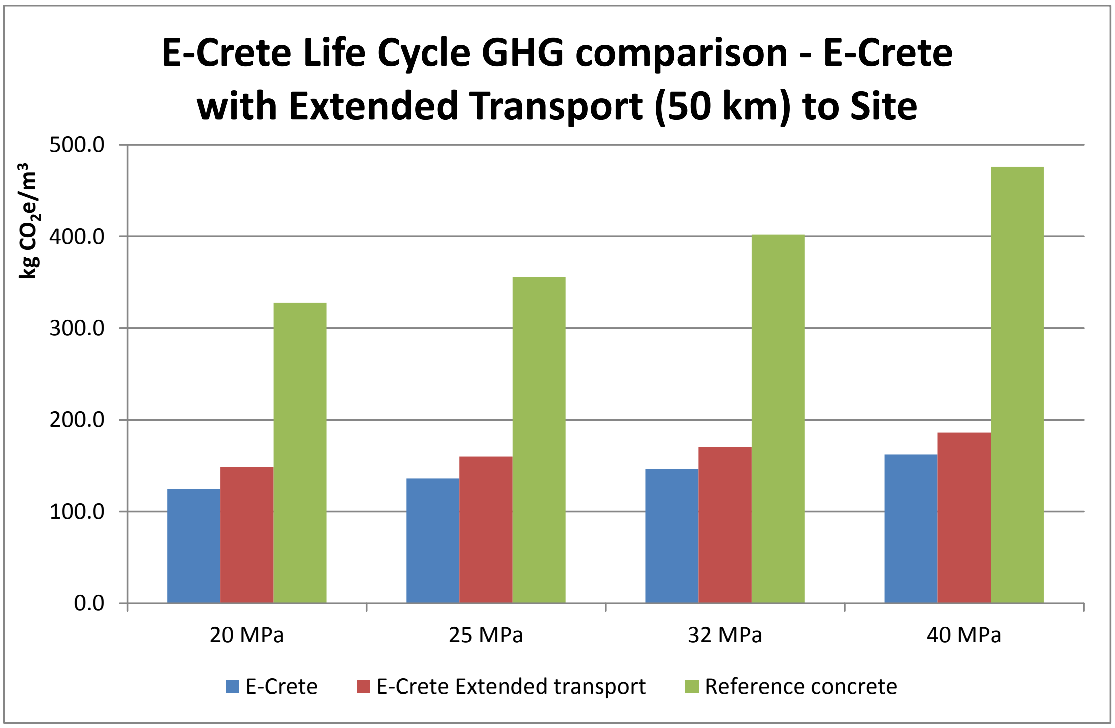

Figure 12. Sensitivity analysis: Effect of transport distance to site on E-Crete emissions

6 Conclusions

The reduction in greenhouse gas emissions for E-Crete compared to standard concrete are primarily attributed to savings achieved through the use of a geopolymer binder. The E-Crete binder (activator, fly ash & GGBFS) has ca. 80% lower embodied greenhouse gas intensity than an equivalent amount of ordinary Portland cement binder used in reference concrete of a similar compressive strength.

When considering the complete life cycle the benefits are somewhat diluted by shared non-binder materials and processes such as transport to site, application, demolition and end-of-life processing. The life cycle greenhouse gas emissions of E-Crete are 62%-66% lower than the GBCA's reference concrete mixtures of equal compressive strength.

E-Crete can also assist projects in achieving Green Star credits due to its:

- substantial reduction in Portland cement content
- use of captured and reclaimed water (up to 100%)
- coarse aggregate replacement (up to 100%), and
- fine aggregate replacement (up to 15%).

7 Limitations

This study presents a full life cycle comparison of specific concrete mixtures: E-Crete and a standard Portland cement concrete reference. Other concrete mixtures can be designed to meet the functional criteria such as compressive strength. Therefore, when attempting to determine the benefits of E-Crete for a particular project, it is essential to have a clear understanding of the reference concrete.

In order for the results of this LCA to be useful for a broad audience some simplifications in the functional unit and life cycle model had to be incorporated:

- The key functional parameter considered is compressive strength. Other parameters, such as tensile strength, durability, fire resistance, chemical resistance, aesthetics, etc. are considered secondary functions. Any differences in functionality – other than compressive strength – between E-Crete and standard concrete are considered non-essential for the purpose of this study.
- There can be a variation in materials and processes used in the manufacture and life cycle of concrete products. For example:
    - Different cements will vary in emissions intensity; in Australia by up to an estimated 20% from the average. (This estimate is based on start2see's experience and qualitative analysis of the Australian cement industry.) These potential differences

between cements can have a material impact on the results of the LCA for standard concrete, although E-Crete's emissions profile will always be lower than that of the reference mixtures currently defined in the GBCA's concrete credit (GBCA 2012).

- Different types of aggregates will require more or less energy to extract, crush and transport to a concrete plant. Unless aggregates are carted in over large distances (>900 km), the conclusions of this LCA are not significantly affected.

Although the principles of ISO14040:2006 and ISO14044:2006 have been applied, this LCA report does not claim to strictly comply with these standards.

References

ADAA 2012, *Use of fly-ash to achieve enhanced sustainability*, Technical Note 11, Ash Development Association of Australia, Wollongong

Commonwealth of Australia 2010, National Waste Overview 2010, Department of Environment, Water, Heritage and the Arts (DEWHA), Environmental Protection and Heritage Council (EPHC), Barton

Commonwealth of Australia 2011, Establishing the eligibility of emissions-intensive trade-exposed activities, Commonwealth of Australia, Barton

GBCA 2012, *Mat-4 Concrete, Revised concrete credit issued 16 May 2012*, Green Building Council of Australia, Sydney

Duxson P, Provis L, Lukey G & Van Deventer J 2007, "The role of inorganic polymer technology in the development of 'green concrete'", Cement and Concrete Research, 37: pp. 1590-1597.

Fawer M, Concannon M & Rieber W 1999, 'Life Cycle Inventories for the Production of Sodium Silicates' International Journal of LCA, 4 (4) pp. 207–212

Flower DJM, Sanjayan JG 2007, 'Green House Gas Emissions due to Concrete Manufacture' International Journal of LCA, 12 (5) pp. 282–288

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, 2007: Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Heidrich C, Hinczak I, and Ryan B 2005, 'SCM's potential to lower Australia's greenhouse gas emissions profile', Iron and Steel Slag Products: A Significant Time of Scarcity, Australasian Slag Association Conference, March 2005 (papers published on CD), Sydney

Hyder Consulting 2009, Waste and Recycling in Australia, Report to the Department of the Environment, Water, Heritage and the Arts, Amended report version 19 November 2009, Barton

Kenway, SJ et al. 2008, Energy use in the provision and consumption of urban water in Australia and New Zealand, CSIRO and Water Services Association of Australia, Canberra

McGuire, E et al. 2011, 'Geopolymer Concrete: Is there an alternative and viable technology in the concrete sector which reduces carbon emissions?', Paper presented to *Concrete 2011: Building a sustainable future*, Perth, 12-14 October

McLellan, BC et al. 2011, 'Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement', Journal of Cleaner Production, no. 19 pp. 1080-1090

McRobert J 2010, CO2 Emission Factor Study, Report prepared for Sustainable Aggregates South Australia

Turner L and Collins F 2012, 'Geopolymers: A greener alternative to Portland cement?', *Concrete in Australia*, Volume 38, no. 1 pp. 49-56

WHD Microanalysis Consultants Ltd, 2012a, *Understanding cement: Carbonation of concrete*, viewed 19 September 2012 <www.understanding-cement.com/carbonation.html>

WHD Microanalysis Consultants Ltd, 2012b, *Understanding cement: Glossary of cement, concrete and SEM terminology – Free Lime*, viewed 19 September 2012 <www.whd.co.uk/Understanding%20Cement/cementandconcret.html>

Worrell et al. 2001, 'Carbon dioxide emissions from the global cement industry', Annual Review of Energy and the Environment, Vol. 26, pp. 303-329

Appendix A. Cement emissions

Average greenhouse gas emissions of cradle-to-gate cement production in Australia are not directly reported by the industry sector. The industry does report average emissions per tonne of cementitious material, but this data is likely to cover only direct emissions and is not readily translatable to Portland cement. Therefore, greenhouse gas emissions from Portland cement are estimated by creating a model of the various components that make up cement production.

Firstly, the following composition for Portland cement has been assumed:

- Clinker 90.0%
- Gypsum 5.0%
- Mineral addition 5.0%

This is a reasonable assumption for cement[10]. The maximum percentage of mineral addition in cement allowed according to AS3972:2010 is 7.5%. The presumed mineral addition is raw (milled) limestone.

The raw materials for cement are typically ground together in a (ball) mill. The electricity consumption of the cement grinding step was estimated at 28-55 kWh/t product (see Figure 13 overleaf). In this study, an average towards the middle end of the range has been applied (40 kWh/t). ACM primarily sources its cement from South Australia, therefore the South Australian emission factor for electricity has been applied (0.79 kg CO_2e/kWh). In order to avoid complicating the comparison, this factor was also applied to cement used for the reference concrete.

Table 13. Emissions intensity of cement

Material	Contribution (t / t)	Emission factor	Contribution to cement Emissions intensity
Clinker	0.900 x	0.957 t CO_2e/t	0.837 t CO_2e/t
Gypsum	0.050 x	0.183 t CO_2e/t	0.009 t CO_2e/t
Mineral addition	0.050 x	0.036 t CO_2e/t	0.003 t CO_2e/t
Cement grinding	1.000 x	0.032 t CO_2e/t	0.032 t CO_2e/t
Portland Cement			**0.904 t CO_2e/t**

[10] Boral: Blue Circle® GP Cement is manufactured from Portland cement clinker and gypsum and up to 5% of AS 3972 approved additions. (Source accessed on 11 October 2012: www.boral.com.au/productcatalogue/product.aspx?product=2328)

The emissions associated with the cradle-to-gate production of each of the raw materials are based on data from various literature sources, see the table below.

Table 14. Data sources for cement manufacturing components

Material	Data	Original Source
Clinker	Carbon emission intensity	Commonwealth of Australia, Establishing the eligibility of emissions-intensive trade-exposed activities, Barton, March 2011
Gypsum	Energy used in production	CRC for Waste Management and Pollution Control
Mineral addition	Energy used in production	Kellenberger D., Althaus H.-J., Jungbluth N., Künniger T. (2007) Life Cycle Inventories of Building Products. Final report ecoinvent data v2.0. Volume: 7. Swiss Centre for LCI, Empa - TSL. Dübendorf, CH.
Cement grinding	Electricity used in production	Worrell et al., Carbon dioxide emissions from the global cement industry. Annual Review of Energy and the Environment, Vol. 26: 303-329, November 2001

TABLE 2 Energy consumption in cement making processes and process types[a]

Process step	Fuel use (GJ/t of product)	Electricity use (kWh/t of product)	Primary energy (GJ/t of cement)
Finish grinding[c]			
Ball mill		55	0.60
Ball mill/separator		47	0.51
Roller press/ball mill/separator		41	0.45
Roller press/separator/ ball mill		39	0.43
Roller press/separator		28	0.31

[a]Specific energy use is given per unit of throughput in each process. Primary energy is calculated per tonne of cement, assuming portland cement (containing 95% clinker), including auxiliary power consumption. NA, Not applicable.

[b]Primary energy is calculated assuming a net power generation efficiency of 33% (LHV).

[c]Assuming grinding of Portland cement (95% clinker, 5% gypsum) at a fineness of 4000 Blaine.

Figure 13. Cement mill energy use (Worrell et al. 2001)