Open access • Journal Article • DOI:10.1007/S11367-009-0105-5

Impact of fly ash content and fly ash transportation distance on embodied greenhouse gas emissions and water consumption in concrete — Source link

Katherine R. O'Brien, Julien Ménaché, Liza O'Moore

Institutions: University of Queensland

Published on: 04 Jul 2009 - International Journal of Life Cycle Assessment (Springer-Verlag)

Topics: Fly ash, Properties of concrete, Portland cement, Life-cycle assessment and Cement

Int J LCA-Revisions Submitted 14 May 2009, 10 pages, 2 figures, 4 tables, 7 equations

Impact of fly ash content and fly ash transportation distance on embodied greenhouse gas emissions and water consumption in concrete

Kate R. O'Brien[1*], Julien Ménaché[2], and Liza M. O'Moore[2]

[1]Division of Environmental Engineering, University of Queensland, Brisbane 4072, Australia

[2]Division of Civil Engineering, University of Queensland, Brisbane 4072, Australia

***Corresponding author** (k.obrien@uq.edu.au)

Abstract

Background, Aims and Scope

Fly ash, a by-product of coal-fired power stations, is substituted for Portland cement to improve the properties of concrete, and reduce the embodied greenhouse gas (GHG) emissions. Much of the world's fly ash is currently disposed of as a waste product. While replacing some Portland cement with fly ash can reduce production costs and the embodied emissions of concrete, the relationship between fly ash content and embodied GHG emissions in concrete has not been quantified. The impact of fly ash content on embodied water is also unknown. Furthermore, it is not known whether a global trade in fly ash for use in concrete is feasible from a carbon balance perspective, or if transport over long distances would eliminate any CO_2 savings. This paper aims to quantify GHG emissions and water embodied in concrete (f'_c=32 MPa) as a function of fly ash content, and to determine the critical fly ash transportation distance, beyond which use of fly ash in concrete increases embodied GHG emissions.

Materials and Methods

This paper used previously published and reported data for GHG emissions and water usage in cement production, quarries, transportation and concrete batching to quantify the embodied GHG emissions (CO_2-equivalent) and water in concrete, and the critical transportation distance for fly ash.

Results

Fly ash content alone is not a good indicator of embodied emissions in concrete; increasing fly ash content only reduces embodied emissions when there is a corresponding reduction in the mass of Portland cement used. The total embodied GHG emissions in concrete ($GHG_{concrete}$, kg CO_2-equivalent m^{-3}) can be determined from the mass of Portland cement used ($mass_{cement}$, t m^{-3}): $GHG_{concrete}$=66+790.7 $mass_{cement}$. This equation can be used to determine the reduction in Portland cement required to meet specific GHG emissions targets for concrete, if the Portland cement is replaced by fly ash sourced within 100 km of a concrete batching plant. Fly ash content has little effect on embodied water, which was 2.7-4.1 m^3 water per m^3 of concrete.

Discussion

Fly ash can be transported more than 11 000 km by articulated truck, 47 000 km by rail and 54 000 km by sea, and still result in a net reduction in GHG emissions if used to replace Portland cement in concrete. At least 70 % of GHG emissions embodied in concrete were due to cement production, even for fly ash content as high as 40 %. Aggregate production accounted for 17-25 % of embodied GHG emissions. While transport of concrete from batching plant to site represented only 3-5 % of GHG emissions, this distance is subject to wide variability and hence can be a source of variation in total embodied GHG emissions. Water used in quarrying aggregate is both the largest and the most variable quantity of water used in concrete production, and accounted for at least 89 % of water consumption for all mix designs considered in this study.

Conclusions

While this study used values applicable to Brisbane, Australia, results are presented in a generalised form for ready adaptation to other conditions, for example different distances to raw materials sources, transport emissions factors etc.

Recommendations and Perspectives

A global trade in fly ash has the potential to reduce GHG emissions embodied in concrete, if the fly ash is used to reduce the consumption of Portland cement per m^3 of concrete. Increasing fly ash usage under these conditions will reduce both the volume of fly ash disposal and the GHG emissions from the concrete industry. Efforts to reduce water consumption in the concrete industry should focus on quarrying processes, and on finding replacement materials with lower embodied water, which may include recycled aggregate. While this study has quantified the GHG emissions and water embodied in concrete as a function of fly ash content, a full life cycle study of concrete is required to determine the full impact of substituting fly ash for Portland cement. Structural characteristics, life span and operational requirements of concrete should also be considered in any decision to alter cement and fly ash content.

Keywords: concrete, fly ash, cement, aggregate, life cycle assessment, embodied water, embodied emissions, greenhouse gas emissions.

Introduction

The concrete industry is a major source of greenhouse gas (GHG) emissions. Approximately 80 % of GHG emissions embodied in concrete are from the production of Portland cement (Flower and Sanjayan 2007), which releases an average of one tonne of carbon dioxide equivalent (CO_2-e) per tonne of cement produced (Malhotra, 2002a). Worldwide, Portland cement production contributes to seven percent of the global GHG emissions (Malhotra, 2002a). In Australia, total GHG emissions from cement production increased by 5.2 % between 1990 and 2005 (AGO 2007). Concrete usage is expected to increase in the future, with the ongoing industrialisation of developing countries such as China and India (Mehta, 2002, Kumar and Patil, 2006). Major changes to the GHG emissions associated with Portland cement are unlikely; hence reducing the consumption of Portland cement by using replacement materials remains the main path for reducing GHG emissions from the concrete industry in the short term (Mehta, 2002).

Substitution of fly ash for a portion of Portland cement can reduce GHG emissions embodied in concrete (Dhir, 2006, Flower and Sanjayan 2007). Flyash is a by-product of coal-fired power plants, and has been used in concrete since the 1930s due to durability and structural benefits (Marsh, 2003). Because of its low permeability, fly ash concrete is less sensitive to chloride, sulphate and carbonation attacks (Dhir, 2006). Moreover, incorporating fly ash in concrete significantly reduces cracking due to thermal stresses, because the heat of hydratation is lowered (Malhotra, 2002b). The consistency is also improved and, if cured well, the strength development is enhanced (Dhir, 2006).

Blended cements used in concrete currently incorporate 15% to 30% fly ash (Marsh 2003). This can be increased to 50%-60% for some particular applications, by using high volume fly ash (HVFA) concrete (Malhotra and Mehta, 2002). Fly ash can also be used to replace 100% of the Portland cement in concrete in a relatively new type of concrete called geopolymer concrete (Kong et al., 2007).

The global output of fly ash is approximately 700-1000 Mt per year, increasing every year in developing countries (Dhir 2006, Kumar and Patil, 2006, Malhotra 2006). Worldwide, about half of the world's annual fly ash production is currently disposed of as a waste product (Dhir, 2006). In Australia, approximately 10 % of fly ash is used in the construction industry, and the remainder is generally disposed of in landfill or ash dams (Wang and Wu, 2006). Disposal of fly ash is becoming increasingly difficult, due to the land area required and the potential for leaching of heavy metals into aquifers and waterways (Foner et al. 1999, Bhattacharjee and Kandpal 2002, Sushil and Batra 2006). Fly ash is widely available on a global basis, and utilisation of fly ash in concrete has the potential to reduce disposal issues.

While previous studies have confirmed that substituting fly ash for Portland cement reduces the embodied GHG emissions in concrete (Flower and Sanjayan 2007, Malhotra 2006, Mehta 2002), a relationship between embodied emissions and fly ash has not been determined. In particular, it is frequently assumed that increasing fly ash content will reduce embodied emissions in concrete, but this has not been verified. Furthermore, the GHG emissions associated with large scale transportation of fly ash have not been investigated. The concrete industry also uses significant amounts of water and aggregates and is, in total, the largest user of natural resources in the world (Mehta, 2002). However, the impact of fly ash substitution on net water consumption has not been determined. The purpose of this study was to quantify the effect of fly ash substitution on GHG emissions and water embodied in concrete, and to determine how far fly ash can be transported for use in concrete, and still confer a net saving in GHG emissions compared to using Portland cement. This information is needed to assess how water consumption and GHG emissions can be reduced by the concrete industry on a global scale. A sensitivity analysis was performed to assess how variability in key parameters affects the results.

1. Methods

Decomposition analysis was used to determine the magnitude and source of GHG emissions produced and water consumed during the manufacture and transport of one cubic meter of concrete (Figure 1), for fly ash content ranging from 0 to 40 %. These mix designs were sourced from two different Brisbane ready-mixed concrete batch plants (Table 1).

The quantities of water, total cementitious material and fine and course aggregate vary between the mixes, and do not necessarily follow the mass of fly ash in a continuous manner (Table 1). This reflects the complex nature of concrete mix design, whereby different adjustments to water, cementitious material and aggregate content are required for even small changes in aggregate size distribution or fly ash content. While all mixes considered here have the same target characteristic compressive strength (32 MPa), other factors affecting workability may need to be adjusted as fly ash quantity is increased. For example slump, a measure of ease of placement or workability, is controlled through the addition of water and chemical admixtures, but the addition of excess water will decrease compressive strength. Fly ash itself, due to it fineness, also has an impact on slump. Changing the quarry source of coarse and fine aggregates can alter water demand and workability.

The Mix B 25% and 40% fly ash mix designs illustrate these issues. Both these mixes are supplied from the same batching plant with the same aggregate sources, and both have a characteristic compressive strength of 32 MPa. However the total cementitous content is much higher for the 40 % fly ash content mix than for the 25% fly ash mix; the 40 % fly ash mix also has a higher content of Portland cement, and significantly less fine aggregate. This is due to the combined impact of water content and fines content (including fine aggregate, fly ash and Portland cement) on slump. Initial mixes with 40% fly ash and 0.320 t m^{-3} cementitious content proved difficult to place (pour), so a commercial decision was made to increase the slump from 80 mm to 100 mm. This required the addition of extra water, which then required additional cementitious content to ensure that the target compressive strength of 32 MPa was maintained.

The impact of fly ash transportation on GHG emissions from concrete was determined for three transportation modes: road, sea, and rail. For each case, the "critical fly ash transportation distance" was determined; fly ash transported greater than that distance would cause a net increase in the GHG emissions per m^3 of concrete, compared to using Portland cement. All GHG emissions are reported as CO_2-equivalent (CO_2-e).

2. Total greenhouse gas (GHG) emissions

The total GHG emissions embodied in concrete ($GHG_{concrete}$, kg CO_2-e m^{-3}) were quantified from the sum of the emissions associated with production of cement, aggregates and fly ash (GHG_{raw_mtls}, kg CO_2-e m^{-3}), and the emissions associated with transport of raw materials to the batching plant ($GHG_{transport\_batch}$, kg CO_2-e m^{-3}) and transport of concrete to site ($GHG_{transport\_site}$, kg CO_2-e m^{-3}), as shown in Fig. 1:

$$GHG_{concrete} = GHG_{raw\_mtls} + GHG_{transport\_batch} + GHG_{transport\_site} \quad (1)$$

The GHG emissions released during the production of raw materials (GHG_{raw_mtls}, kg CO_2-e m^{-3}, Table 1) were determined from the mass of the raw materials used (*mass*, t m^{-3}), and the emissions factors (ε, kg CO_2-e t^{-1}, Table 2) for each production process:

$$GHG_{raw\_mtls} = \sum_{\substack{i=coarse\ aggregate \\ fine\ aggregate \\ cement \\ flyash}} mass_i \quad \varepsilon_i \quad (2)$$

Since fly ash is a waste product, it does not require energy to produce. Heidrich et al., 2005 estimated that collection of fly ash at the power stations results in emissions of 0.006 CO_2-e kg per tonne of fly ash. However fly ash will be collected at the power stations for air quality reasons, regardless of whether it is used in concrete, and so this value should not be included in the fly ash emissions factor. When collection and transport are excluded, the emissions factor for fly ash is less than 1 kg CO_2-e kg per tonne (Heidrich et al. 2005). This does not account for the emissions avoided, by removing the need for disposal of fly ash. Thus the true emissions factor for fly ash is likely to be negative. However, there is no published data on the emissions associated with fly ash disposal, and this value is likely to vary widely depending on disposal methods. Hence here we use a conservative emissions factor of 0 for fly ash (Table 2), which will be an overestimate of the true emissions factor. GHG emissions associated with admixtures, batching of concrete and concrete operations on site are neglected, since they are difficult to quantify and account for less than 3 % of GHG emissions embodied in concrete (Flower and Sanjayan 2007). The emissions associated with these processes are also unlikely to be affected by the distance of fly ash transportation.

The GHG emissions associated with transportation of raw materials to the batching plant, and transportation of concrete to site were determined from the mass of material (*mass*, t m^{-3}, Table 1), the distance transported (*X*, km, Table 2) and the emissions factor for the transport mode used ($\varepsilon_{transport}$, kg CO_2-e t^{-1} km^{-1}, Table 3):

$$GHG_{transport\_batch} = \sum_{\substack{i=coarse\ aggregate \\ fine\ aggregate \\ cement \\ flyash}} mass_i \quad \varepsilon_{transport\_i} \quad X_i \quad (3)$$

$$GHG_{transport\_site} = \rho_{concrete} \quad \varepsilon_{transport\_concrete} \quad X[km\ to\ site] \quad (4)$$

where $\rho_{concrete}$ is the density of concrete (2.33-2.44 t m^{-3}, Table 1). Aggregates and cement were assumed to be transported to the batching plant by articulated truck. Concrete was assumed to be transported 20 km to site by rigid truck. Empty truck returns have not been taken into account, because the emission factors are given per tonne of freight, meaning that the emissions from an empty truck are negligible. While Flowers et al. (2007)

included returned journeys, their estimates of batch to site transportation GHG emissions were similar to the values generated here.

3. GHG emissions as a function of fly ash and cement content

For mix A, total GHG emissions embodied in concrete ($GHG_{concrete}$, kg CO_2-e m^{-3}) decreased with increase in fly ash content (x_{FlyAsh}, kg fly ash per kg total cementitious material): $GHG_{concrete}$=320-253 x_{FlyAsh} (Fig. 2a). This was because fly ash, which has an emissions factor of zero, was substituted for Portland cement, which has an emissions factor of 790 kg CO_2-e t^{-1} (Table 2).

However when fly ash content was increased from 25 % to 40 % in mix B, the total cementitious material and mass of Portland cement also increased, to adjust the pouring properties of the concrete (Table 1). Hence the total embodied GHG emissions were higher for the mix B with 40 % fly ash than for the mix B with 25 % fly ash (Fig. 2a). This demonstrates that increasing the fly ash content of concrete will only reduce embodied GHG emissions if it leads to a decrease in the mass of Portland cement used. Thus it is more accurate to define $GHG_{concrete}$ as a function of Portland cement content ($mass_{cement}$, t m^{-3}), rather than as a function of fly ash content. For 32 MPa concrete, the values in Tables 1-3 substituted into Eqns 1-4 yielded the following relationship (Fig. 2b):

$$GHG_{concrete} = GHG_{no\_cement}\left[\frac{kgCO_2 - e}{m^3\ concrete}\right] + mass_{cement}\left[\frac{t\ cement}{m^3\ concrete}\right]GHG_{cement}\left[\frac{kgCO_2 - e}{t\ cement}\right] \quad (5)$$

where GHG_{no_cement} =66 kg CO_2-e m^{-3} is the embodied GHG emissions for concrete in the absence of cement, for fly ash transported 100 km to batching plant, and GHG_{cement} =790.7 kg CO_2-e t^{-1} are the emissions per t of cement, transported 10 km to batching plant. The root mean square error for the difference in $GHG_{concrete}$ calculated from Eqn 1 and from Eqn 5 across all of the mix designs in Table 1 was 0.5 kg CO_2-e m^{-3} (<0.2 %). This variability was driven by the variation in the mass of raw materials across the mix designs (Table 1). The contribution of transport to $GHG_{concrete}$ was very small; transportation of cement 10 km to the batching plant accounted for less than 0.1 % $GHG_{concrete}$ (Table 4). Hence increasing this distance by an order of magnitude would affect $GHG_{concrete}$ by less than 1 %.

Eqn 5 predicts a theoretical minimum of 66 kg CO_2-e m^{-3} embodied GHG in concrete where Portland cement is completely replaced with fly ash. For 32 MPa concrete with a constant cementitious material content of 0.32 t m^{-3} and no fly ash (e.g. mix A, 0 % fly ash, Table 1), $GHG_{concrete}$ =319 kg CO_2-e m^{-3}, which agrees well with the equation generated in Fig. 2a. Thus in the absence of fly ash, cement production accounts for almost 80 % of total concrete emissions (Eqn 5, Table 4), which is consistent with the results of Flower and Sanjayan (2007). Eqn 5 predicts an emissions factor of 256 kg CO_2-e m^{-3} for 32 MPa concrete with 25 % fly ash and a total cementitious material content of 0.32 t, which is within 6 % of the value predicted by Flower and Sanjayan (2007).

These results suggest that rather than stipulating fly ash content for "green" concrete, it would be better to define a specific GHG emissions target, and use Eqn 5 to determine the maximum Portland cement content allowable, assuming replacement with fly ash sourced approximately 100 km from batching plants. For example, Portland cement content must be less than 0.25 t m^{-3} to meet the GHG emissions target of 270 kg CO_2-e m^{-3} for slabs (f'_c =32 MPa), and less than 0.21 t m^{-3} to meet the emissions target of 240 kg CO_2-e m^{-3} (Eqn 5). For constant cementitious material content of 0.32 t m^{-3}, this corresponds to 20 % and 32 % fly ash respectively.

Where an increase in fly ash content is accompanied by a reduction in Portland cement content, the relative contribution of Portland cement to the total embodied emissions in concrete is reduced (Table 4). However even where fly ash content is high (40 %) and Portland cement content reduced proportionally, the emissions from cement production still represent at least 70 % of the total GHG emissions embodied in concrete (Table 4). Hence it is important to continue to reduce the emissions associated with cement production where possible, and for ready- mixed concrete plants worldwide to aim for current best practice.

While small variations in emissions factors for cement and aggregate production will cause sizeable variations in the total GHG emissions, large variations in transport distance will also affect the emissions factor for concrete. In particular, the distance between the batching plant and site can vary widely. Since transport of concrete 20 km to site represents 3-5 % of GHG emissions, total GHG emissions would increase by 12-20 % if the concrete were transported 100 km to site. Even though transport to site represents a relatively small percentage of total emissions, the distance between batch plant and site can vary widely, and hence can have a noticeable effect on variability in emissions. Table 4 can thus be used in conjunction with Equations 1 and 2 to extend these results to production of concrete under conditions different to those considered in this study.

4. GHG emissions as a function of fly ash transport distance

Since fly ash has a negligible emissions factor (Table 2), total fly ash emissions depend on the distance transported to the batching plant (X, km), the transportation emissions factor ($\varepsilon_{transport}$, CO_2-e t^{-1} km^{-1}), and the mass of fly ash used in the concrete (t m^{-3}), which can be determined from the fly ash content and the mass of cement: $mass_{cement}\, x_{FlyAsh}/(1- x_{FlyAsh})$. Hence Eqn 5 can be rewritten:

$$GHG_{concrete} = GHG_{no\_cement\_no\_flyash} + mass_{cement}\left(GHG_{cement} + \frac{x_{flyash}}{(1-x_{flyash})}\varepsilon_{transport} X \right) \quad (6)$$

where $GHG_{no\_cement\_no\_flyash}$ =66 (kg CO_2-e m^{-3}) represents the emissions associated with aggregate production and transport, and transport of concrete to site. For fly ash transported 100 km to the batching plant, Eqn 6 simplifies to $GHG_{concrete}$=66-790.7$mass_{cement}$ (Eqn 5) because transport of fly ash over 100 km makes a negligible contribution to total emissions (Table 4).

Transportation of fly ash to substitute for Portland cement in concrete will result in a net reduction in embodied GHG emissions only when the emissions per tonne of fly ash transported ($\varepsilon_{transport}\, X$) are less than the emissions associated Portland cement production and transport (GHG_{cement}). Hence the critical distance for fly ash transportation ($X_{critical}$, km), beyond which substitution of fly ash for Portland cement will cause an increase in $GHG_{concrete}$, can be written:

$$X_{critical} = \frac{GHG_{cement}}{\varepsilon_{transport}} \quad (7)$$

From Eqn 7, the critical distance for fly ash transportation by articulated truck is greater than 11 000 km (Table 3), i.e. more than a quarter of the way around the world. When transported by rail or sea, fly ash can be transported more than 47 000 km or 54 000 km, respectively, and still reduce the embodied GHG emissions in concrete if used to replace Portland cement (Table 3). The Australian emissions factor for cement production used in this study is one of the lowest in the world (Humphreys and Mahasenan 2002); in other parts of the world, where GHG_{cement} is higher, the critical fly ash transportation distance may be even greater (Eqn 7), although Eqn 7 may need to be adjusted to include local transport emissions factors. This indicates a world-wide commercial trade in fly ash has the potential to reduce the net GHG emissions from the concrete industry.

5. Embodied Water

The volume of water consumed per m^3 of concrete was determined from the sum of water used in the extraction and processing of aggregates, the production of electricity used in cement and aggregate production, and the water directly added in the mix when batching the concrete (Table 1). Water usage in each of these processes is consumptive, as defined by Pfister et al. 2009; water is either evaporated (e.g. to control dust in aggregate production, and as part of the cooling water cycle in power stations), or directly incorporated in the finished product (i.e. concrete). Water usage in concrete plants to wash out aggregates, concrete trucks etc is not considered here, because it is assumed to be recycled rather than consumed. Use of fly ash in concrete may reduce the volume of water used to transport fly ash and dispose of it in ash dams near power stations, however there is large variability in ash management practices, and no published data on water usage in ash dams. In many cases, the water used in ash management may be run-off generated on-site, which must be maintained on site to meet regulatory requirements. Hence the water consumption avoided by incorporating fly ash in concrete rather than disposing of it in ash dams was not considered here.

Estimates of water consumption within quarries vary widely: greater than 1 m^3 per tonne of gravel (Bourgeois et al. 2003), 1.35-1.38 m^3 per tonne of gravel (Ecoinvent 2007) or 2 m^3 per tonne of sand or gravel (SimaPro 2007). Water consumption associated with use of electricity in the production of aggregates and cement is a product of the mass of raw materials used (Table 1), the water consumed in coal-fired power plants (1.95 m^3 MWh^{-1}, Brown et al. 2007), and the electrical energy used in the production of aggregate and cement. Electrical energy accounts for 48 % of emissions associated with fine aggregate production, and 77-80 % of emissions associated with coarse aggregate production (Flower and Sanjayan, 2007). Combined with an electricity emissions factor of 0.001392 t CO_2-e kWh^{-1} (Flower and Sanjayan, 2007) and the aggregate emissions factors in Table 2, these values indicate that average consumption of electrical energy during aggregate production is 4.8 kWh and 23.0 kWh per tonne of fine and coarse aggregate, respectively. While most of the emissions embodied in cement arise from the cement production process and fuel, 0.1 t CO_2-e per tonne of cement can be attributed to electrical power usage (CIF, 2007). Applying an electricity emissions factor of 0.001392 t CO_2-e kWh^{-1} (Flower and Sanjayan, 2007) to this value indicates that approximately 72 kWh of electricity are consumed per tonne of cement produced.

For the mix designs considered here, the embodied water in concrete ranges from 2.7- 3.0 m^3 water per m^3 concrete, (assuming 1.4 m^3 t^{-1} water consumption in aggregate production), to 3.7- 4.1 m^3 water per m^3 concrete

(assuming 2.0 m^3 t^{-1} in aggregate production). The ecological impact of this water consumption will vary according to where the water is sourced, and local availability and usage rates (Pfister et al., 2009). Of the total water consumed during concrete production, aggregate production accounts for 89-94 % and direct usage accounted for 4-7 % of the total water consumed. While Australian power stations are generally water intensive due to the wet-cooling cycle, water associated with production of electricity only accounts for 2-4 % of total embodied water in concrete because the amount of electricity used in cement and aggregate production is small. Hence even if a less water-intensive source of electricity were used in cement and aggregate production, it would have a minimal effect on the embodied water in concrete.

The variation in water consumption between different mix designs was driven primarily by variation in aggregate content, since direct water usage was small by comparison. Coarse and fine aggregate content and water usage will be adjusted with fly ash content at concrete batching plants to ensure correct strength and consistency. However this is not a straightforward of proportional adjustment, but will depend on the size distribution and source of both the aggregate and fly ash, which will vary both within and between batching plants. Hence there is no predictable relationship between fly ash content and embodied water. This is quite different to the effect of fly ash on embodied GHG emissions.

6. Conclusions

Using fly ash in concrete offers numerous structural and environmental advantages (Dhir, 2006), including the reduction of embodied GHG emissions through the replacement of Portland cement. However increasing fly ash content will only reduce emissions to the degree that Portland cement usage is reduced. We have developed an equation to predict embodied emissions in concrete as a function of fly ash content and total mass of cementitious material, which will assist in formulating concrete to meet specific emissions targets. However any change to concrete formulation should also account for the impact of fly ash on structural and operational features, and the specific requirements for each concrete application.

This study has shown that fly ash can be transported very large distances (more than a quarter of the way around the world by road, and much further by rail and sea), and still deliver a net saving in GHG emissions if used to replace Portland cement in concrete. Transport efficiencies and cement emissions factors can vary between locations, and this can be accounted for on a local basis by application of Equations 6 and 7. Regardless of local variability, these results strongly suggest that a global trade in fly ash could reduce GHG emissions from the concrete industry if used to reduce the consumption of Portland cement. These savings may be very large if high volume fly ash concrete is used in the major infrastructure projects underway in the developing world.

Water consumption in quarries accounts for more than 89 % of water embodied in concrete, and hence fly ash content has a negligible effect on embodied water. Reducing water consumption in quarries will reduce the embodied water in concrete, however replacement materials may provide a greater source of reductions. Any assessment of water consumption associated with recycled aggregate materials should also consider the effect of those materials on embodied GHG emissions. Since recycled aggregate can reduce concrete strength (e.g. Xiao et al., 2005), it may require greater cement content, which will affect GHG emissions. Fly ash can be used as a replacement material for fine aggregates in concrete (Foner et al. 1999, Dhir et al., 2006); this may reduce both water and GHG emissions embodied in concrete.

Obstacles to the wide-scale increase of fly ash use in concrete are the variable quality of fly ash, the slow curing rates, and prescriptive specifications that limit the fly ash content (Bhattacharjee and Kandpal 2002, Kumar and Patil 2006, Vargas, 2007).. Finally, this study did not include any analysis of the cost impacts due to increased transportation, and longer construction cycles, because cost analysis is likely to change in the near future, with major changes to carbon pricing under consideration world wide.

This study did not quantify the full impacts of fly ash substitution over the life of concrete. For example, utilising fly ash in concrete reduces the area required for fly ash landfill or dams (Foner et al. 1999, Kumar and Patil 2006), and also reduces the potential for leaching of heavy metals from fly ash into surface or ground water (Iyer and Scott 2001, Sushil and Batra 2006). The study also did not consider transport pollutants other than GHG emissions. Hence there is still a need for a full life cycle study of concrete to determine the full impact of substituting fly ash for Portland cement.

Acknowledgements

The authors wish to thank Des Chalmers at Cement Australia for assistance in locating data, Jay Sanjayan for his helpful review, and Bob Pagan and Marguerite Renouf at UQ for sourcing data from SimaPro and Ecoinvent databases. Two anonymous reviewers provided very helpful comments on this manuscript. We also wish to thank the local concrete supplier for providing mix designs.

References

Apelbaum Consulting Group (ACG) (2007): Australian Transport Facts 2007. Apelbaum Consulting Group Pty Ltd, Incorporating the Centre of Transport, Energy and the Environment, Mulgrave, Victoria Australia April 2007.
Australian Greenhouse Office (AGO) (2007): Analysis of Recent Trends and Greenhouse Indicators 1990 to 2005, Commonwealth of Australia
Bhattacharjee U, Kandpal TC (2002): Potential of fly ash utilisation in India. Energy 27, 151–166
Bourgeois F, Baudet G, Bizi M, Gaboriau, H (2003): Conditioning circuit analysis for slimes management in quarries. Chemical Engineering Res. Des 81 (A9), 1158-1164
Brown P, Searles M, Cottrell A, Scaife P (2007): LCA of the Queensland Electricity Grid (Year ending 2004), Co-operative Research Centre for Coal in Sustainable Development, Technology Assessment Report 61
Cement Industry Federation (CIF) (2007): 2007 Review of the Technology Pathway for the Australian Cement Industry 2005 - 2030
Dhir R (2006): The potential of fly ash: the future looks bright. Concrete. 40 (6), 68-70
Dhir R, Dyer T, Paine K (2006): Appropriate use of sustainable construction materials. Concrete. 40 (9), 20-24
Ecoinvent data base. 2007. Swiss Centre for Life Cycle Inventories
Flower DJM, Sanjayan JG (2007): Green House Gas Emissions due to Concrete Manufacture. Int J LCA. 12(5), 282-288
Foner HA, Robl TL, Hower, JC, Graham, UM (1999) Characterization of fly ash from Israel with reference to its possible utilization. Fuel 78, 215-223
Heidrich C., Hinczak I. & Ryan B. (2005): Supplementary Cementitious Materials (SCMs) potential to lower Greenhouse Gas emissions for Australia. Concrete 05, Melbourne, Victoria, Australia, Concrete Institute of Australia.
Humphreys K, Mahasenan M (2002): Climate change Substudy 8: Towards a sustainable cement industry. World Business Council for Sustainable Development (WBCSD)
Iyer and Scott 2001
Kong DLY, Sanjayan JG, Sagoe-Crentsil, K (2007): Comparative performance of geopolymers made with metakaolin and fly ash after exposure to Elevated Temperatures. Cement and Concrete Research 37(12), 1583-1589
Kumar S, Patil CB (2006): Estimation of resource savings due to fly ash utilization in road construction. Resources, Conservation & Recycling 48, 125-140
Malhotra VM, Mehta, PK (2002): High-Performance, High-Volume Fly Ash Concrete: Materials, Mixture Proportioning, Properties, Construction Practice and Case Histories, Supplementary Cementing Materials for Sustainable Development. Ottawa, Canada, 101pp, as cited in Malhotra 2006
Malhotra VM (2002a): Sustainable Development and Concrete Technology. Concrete International 24 (7), 22
Malhotra VM (2002b): High-Performance High-Volume Fly Ash Concrete. Concrete International 24 (7), 30-34
Malhotra VM (2006): Reducing CO_2 Emissions. Concrete International 28 (9), 42-45
Marsh B (2003): High-volume ash concrete. Concrete 37 (4), 54-56
Mehta, PK (2002): Greening of the Concrete Industry for Sustainable Development. Concrete International 24 (7), 23-28
Pfister S, Koehler, A, Hellweg, S (2009): Assessing the environmental impacts of freshwater consumption in LCA. Environmental Science and Technology, published online April 2009
SimaPro 2007 LCA software. RMIT Centre for Design
Sushil S, Batra, VS (2006): Analysis of fly ash heavy metal content and disposal in three thermal power plants in India. Fuel 85, 2676-2679
Vargas A (2007): A Designer's View of Fly Ash Concrete. Concrete International, 29 (2), 43-46
Wang S, Wu H (2006): Environmental-benign utilisation of fly ash as low-cost adsorbents. Journal of Hazardous Materials B136, 482-501
Xiao J, Li J, Zhang C (2005): Mechanical properties of recycle aggregate concrete under uniaxial loading. Cement and Concrete Research 35, 1187-1194

Fig. 1: Source of greenhouse gas (GHG) emissions during manufacture and transportation of concrete. Full fuel cycle GHG emissions are calculated for each transport stage.
Fig. 2: GHG emissions factor for concrete (f $'_c$ =32 MPa), with fly ash transported 100 km to batching plant by articulated truck, as a function of a) fly ash content; b) Portland cement content.

Table 1: Commercial mix design for a characteristic strength f'$_c$ = 32 MPa; superscript denotes two different sources of mix design.
Table 2: Emission factors for production of concrete raw materials, and typical transport distances to batching plant (* Humphreys and Mahasanen, 2002, ** Heidrich et al., 2005, *** Flower and Sanjayan, 2007).
Table 3: Full fuel cycle emissions factors for transportation, calculated from ACG, 2007, and critical fly ash transportation distance, calculated from Eqn 7 using full fuel cycle emissions factors.
Table 4: Percentage of embodied greenhouse gas emissions ($GHG_{concrete}$) from each stage of concrete production and transport to site, for three levels of fly ash content (fly ash transported 100 km to batching plant by articulated truck).

Table 1

Fly Ash content (%)	Target Slump (mm)	Mass of Portland Cement (t / m^3 concrete)	Mass of Fly Ash (t / m^3 concrete)	Mass of Water (t / m^3 concrete)	Mass of coarse Aggregates (t / m^3 concrete)	Mass of fine Aggregates (t / m^3 concrete)
0 [A]	80	0.324	0	0.184	1.010	0.919
16 [A]	80	0.273	0.051	0.181	1.011	0.920
20 [A]	80	0.258	0.066	0.183	1.011	0.920
25 [A]	80	0.243	0.081	0.180	1.007	0.916
30 [A]	80	0.227	0.096	0.185	1.010	0.914
40 [A]	80	0.192	0.128	0.177	1.000	0.910
25 [B]	80	0.240	0.080	0.185	0.990	0.940
40 [B]	100	0.255	0.165	0.200	1.070	0.640

Table 2

	Cement	Fly ash	Coarse aggregate	Fine aggregate
Emissions factor ε (kg CO_2-e t^{-1})	790 *	0**	41***	14***
Distance to batching plant *X*	10 km	100 km	10 km	10 km

Table 3

Transport mode	Emissions factor ε kg CO_2-e km^{-1} t^{-1}	Critical transportation distance for flyash $X_{critical}$ km
Rigid truck freight	0.209	3 800 km
Articulated truck freight	0.071	11 100 km
Rail freight	0.0166	47 600 km
Sea freight	0.0146	54 200 km

Table 4

Fly ash content	Portland cement production	Portland cement transport	Aggregate production	Aggregate transport	Fly ash transport	Transport to site
0 (mix A)	79 %	<0.1 %	17 %	<1 %	0	3 %
25 % (mix A)	74 %	<0.1 %	21 %	<1 %	<1 %	4 %
25 % (mix B)	74 %	<0.1 %	21 %	<1 %	<1 %	5 %
40 % (mix A)	70 %	<0.1 %	25 %	<1 %	<1 %	4 %
40 % (mix B)	76 %	<0.1 %	20 %	<1 %	<1 %	4 %

Fig. 1

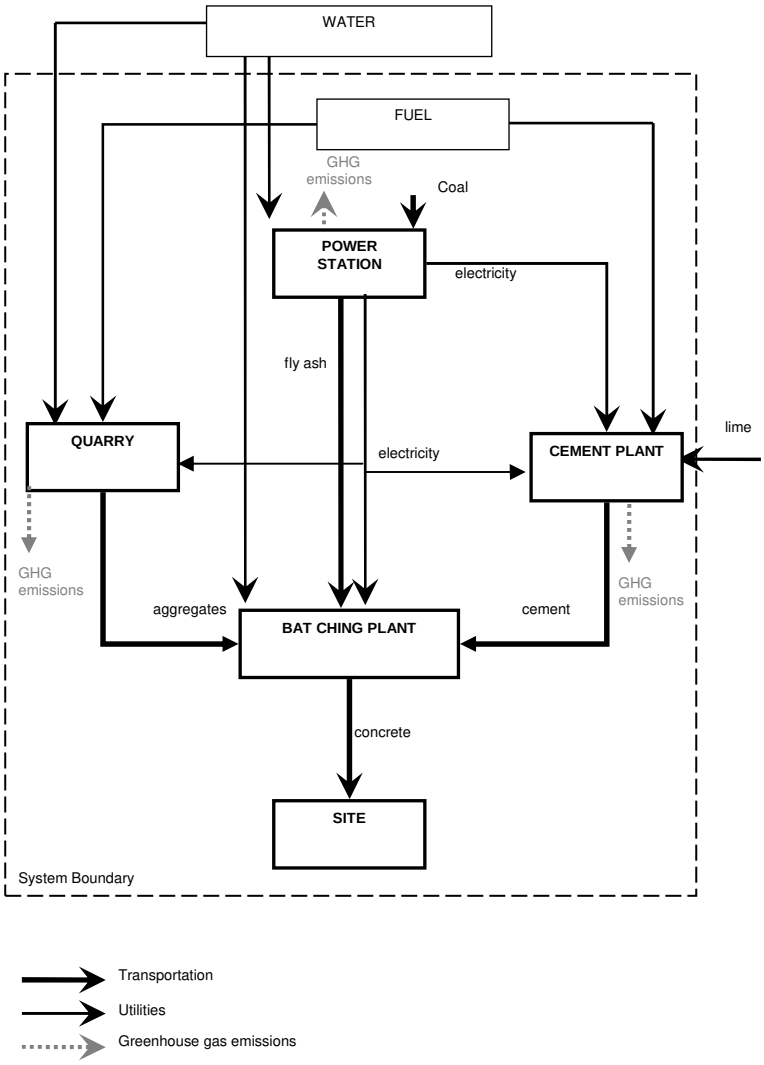
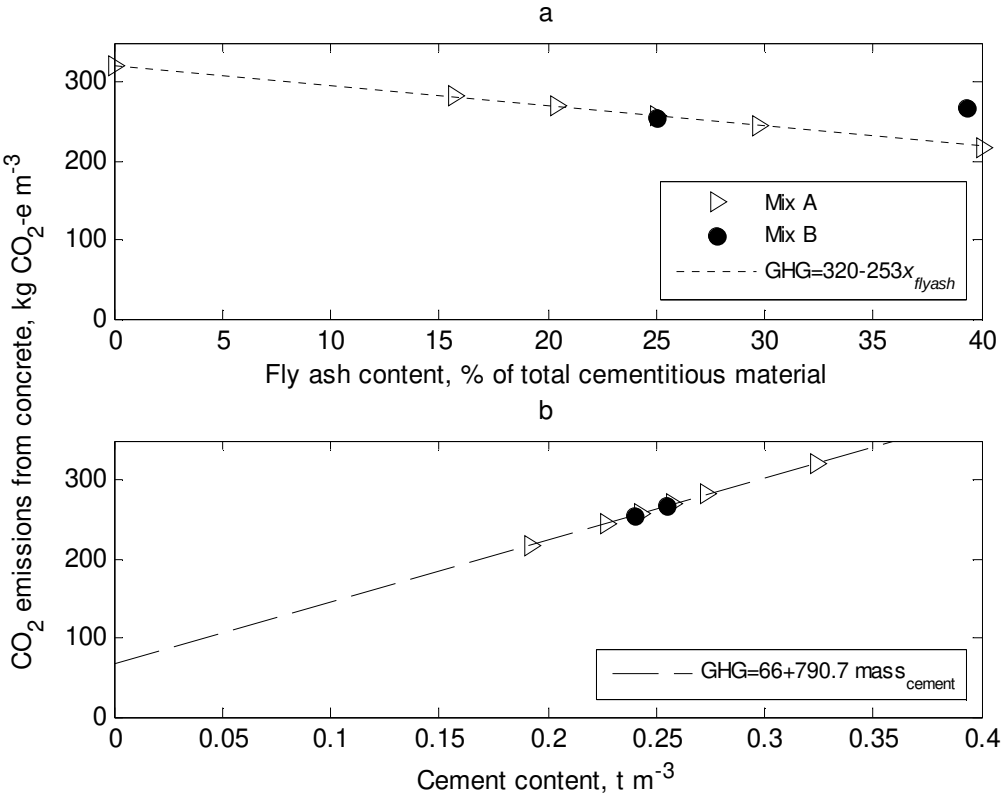

WATER
FUEL
GHG
emissions
Coal
POWER
STATION
electricity
fly ash
QUARRY
electricity
CEMENT PLANT
lime
GHG
emissions
GHG
emissions
aggregates
cement
BAT CHING PLANT
concrete
SITE
System Boundary
Transportation
Utilities
Greenhouse gas emissions

Fig. 2


a
300
200
100
0
0
5
10
15
20
25
30
35
40
Mix A
Mix B
GHG=320-253x flyash
Fly ash content, % of total cementitious material
b
CO2 emissions from concrete, kg CO2-e m-3
300
200
100
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
GHG=66+790.7 masscement
Cement content, t m-3