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Costs and carbon emissions for Geopolymer pastes in comparison to Ordinary Portland Cement

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ABSTRACT

Geopolymer concrete is seen as a potential alternative to standard concrete, and an opportunity to convert a variety of waste streams into useful by-products. One key driver in geopolymer development is the desire to reduce greenhouse gas emissions from the production of concrete products. This paper presents an examination of the life cycle cost and carbon impacts of Ordinary Portland Cement (OPC) and geopolymers in an Australian context, with an identification of some key challenges for geopolymer development. The results of the examination show that there is wide variation in the calculated financial and environmental "cost" of geopolymers, which can be beneficial or detrimental depending on the source location, the energy source and the mode of transport. Some case study geopolymer concrete mixes based on typical Australian feedstocks indicate potential for a 44-64% reduction in greenhouse gas emissions while the financial costs are 7% lower to 39% higher compared with OPC.

1. INTRODUCTION

Cement production is a significant industrial activity in terms of its volumes and contribution to greenhouse gas emissions. Globally, the production of cement contributes at least 5-7% of CO_2 emissions [1-4], while in Australia, it is estimated that the production of cement accounted for approximately 1.3% of greenhouse gas emissions in 2008 [5, 6].

Fly ash and other by-products of the energy and minerals industry that are currently disposed of as waste, have been the focus of much research into reuse opportunities [7-9] – especially as a supplementary cementitious material in cement [10, 11], and as a feedstock for geopolymers[12, 13]. Beneficial reuse would assist the producers of waste to reduce required storage and rehabilitation costs, as well as providing a minor financial benefit from sale. A number of studies have examined the greenhouse emissions of concrete and cement, and the impact of fly ash content on the total emissions [11, 14]. The original comparisons that were drawn in the literature were largely on the basis of the production step of cement and geopolymer [15, 16]. These studies argued that avoiding the high direct emissions of CO_2 from cement production and reducing some process energy can make the geopolymer greenhouse emissions up to 5-6 times lower than cement [16]. However, the impacts associated with the production, processing and transportation of feedstocks are likely to contribute significantly to the life cycle emissions of the concrete. Hence a life cycle approach to the comparison is warranted. The life cycle approach has recently been applied in a number of studies examining the life cycle impacts of Ordinary Portland Cement (OPC) and concrete production [11, 14, 17-20]. Geopolymer concretes have also been examined [21-24], however these have not addressed specifically the impacts of alternative feedstock combinations, transportation or energy mixes that are addressed in this paper.

The current work seeks to build on the existing literature, by examining the life cycle impacts of geopolymers in comparison to OPC, incorporating the feedstock extraction and production impacts with an examination of the variability of data sourced from the literature. The recent studies that have been completed on geopolymer concretes indicate that there is a potential for 25-45% [23] or 70% [21] reduction in greenhouse gas emissions. Both of these studies utilise the European Ecoinvent lifecycle database, and are set in the European context, whereas this study seeks to quantify the range of potential costs and impacts for geopolymer concretes in Australia. Australia is a useful example as its large resource base, high per capita generation of fly ash and mineral wastes, and large distances make it ideal for testing the benefits of geopolymer concretes that rely on waste product streams, with particular interest in the transportation component.

2. METHODS

If geopolymers are to be a viable competing product to OPC based concretes, they will be required to demonstrate a similar financial cost to the user and / or significant functional, manufacturing or sustainability benefits. In order to be able to compare geopolymers with OPC on a sustainability basis, three headline metrics were chosen. In this case, the energy (direct fuel usage and electricity usage), greenhouse emissions and cost were chosen as three key metrics which are considered to form the main argument for or against the use of geopolymers - notwithstanding the fact that other key indicators have a significant role to play – such as technical performance, leaching, water usage, hazardous materials content, other environmental emissions of production [21] and the amount of waste volume that can be avoided by utilising fly ash in geopolymer or OPC concrete. The three selected metrics are the ones most readily quantified for the situation where the location and exact characteristics of component materials are unknown, especially in these early stages of industrial geopolymer development. Localised pollutants, while important in a sustainability sense, are not quantified here due to the dispersed nature of the system being examined, and the uncertainty of location of those emissions.

Any comparative assessment of geopolymers and OPC-based concrete should ideally be made on the same functional unit – i.e. a concrete, mortar or paste engineered to perform the same key function. For the purpose of providing information that can readily be scaled to any application, the current work examines the production of OPC and geopolymer paste, and the metrics associated with key feedstocks. Values are quoted per tonne of feedstock or per equivalent tonne of OPC. These values can then be readily used to calculate the sustainability impacts of a given formulation of geopolymer, and compared with the equivalent amount of OPC giving comparable performance. Some examples of geopolymer and OPC concretes are shown in this paper, based on mixes found in the literature. This gives an alternative comparison on a practical performance basis.

The energy, cost and emissions metrics are derived using a life cycle approach. For the purpose of this assessment, this implies the impacts for the production of required feedstocks as well as the manufacture of the binder, and any relevant transportation. The importance of this approach is that it allows a valid comparison of the two materials - production impacts alone do not give the full picture of the required "embodied" energy and CO_2 in feedstocks. The mixing, laying and curing of the geopolymer and OPC, and the operational lifetime emissions are not included as they are assumed to be similar for each product. The approach, therefore, may be considered to give a comparable life cycle impact, rather than an absolute impact. This is a useful approach for similar products, as it reduces the time required for the assessment.

The approach taken in this work has not considered formally the durability or service life of geopolymers as opposed to OPC concretes. This was omitted on the grounds that the service life is still yet to be clarified for geopolymers as they are an emerging product. However, the testing of geopolymer concrete under a variety of applications has indicated that the durability and service life is likely to be better than that of traditional concretes. Hence the assumption of equal durability and service life is likely to underestimate the benefit of geopolymers over OPC-based concretes or overestimate the cost. This is especially relevant in applications such as railway sleepers, where a schedule of replacement is expected.

Recycling of end-of-life products have also been neglected for this assessment. It may be assumed that, as for standard concretes, the utilization of recycled geopolymer would largely be in the form of aggregate. There is potential for further research to examine the full life cycle for particular functions (e.g. railway sleepers, sewerage applications, etc.), and with a closer examination of average lifetime and recyclability. The material input diagrams and life cycle processes included in the analysis for geopolymers and OPC respectively are shown in Figures 1 to 4.

Figure 1: Schematic of production of geopolymer concrete

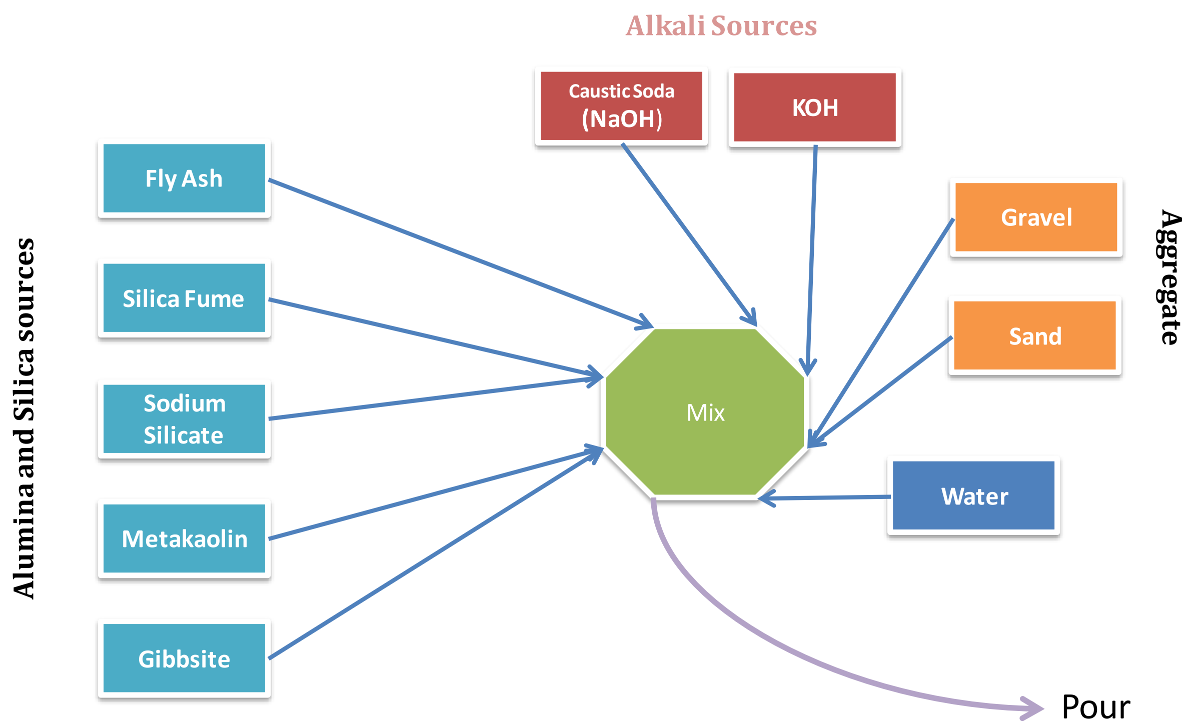


Figure 2: Life cycle stages considered for production of geopolymer feedstock

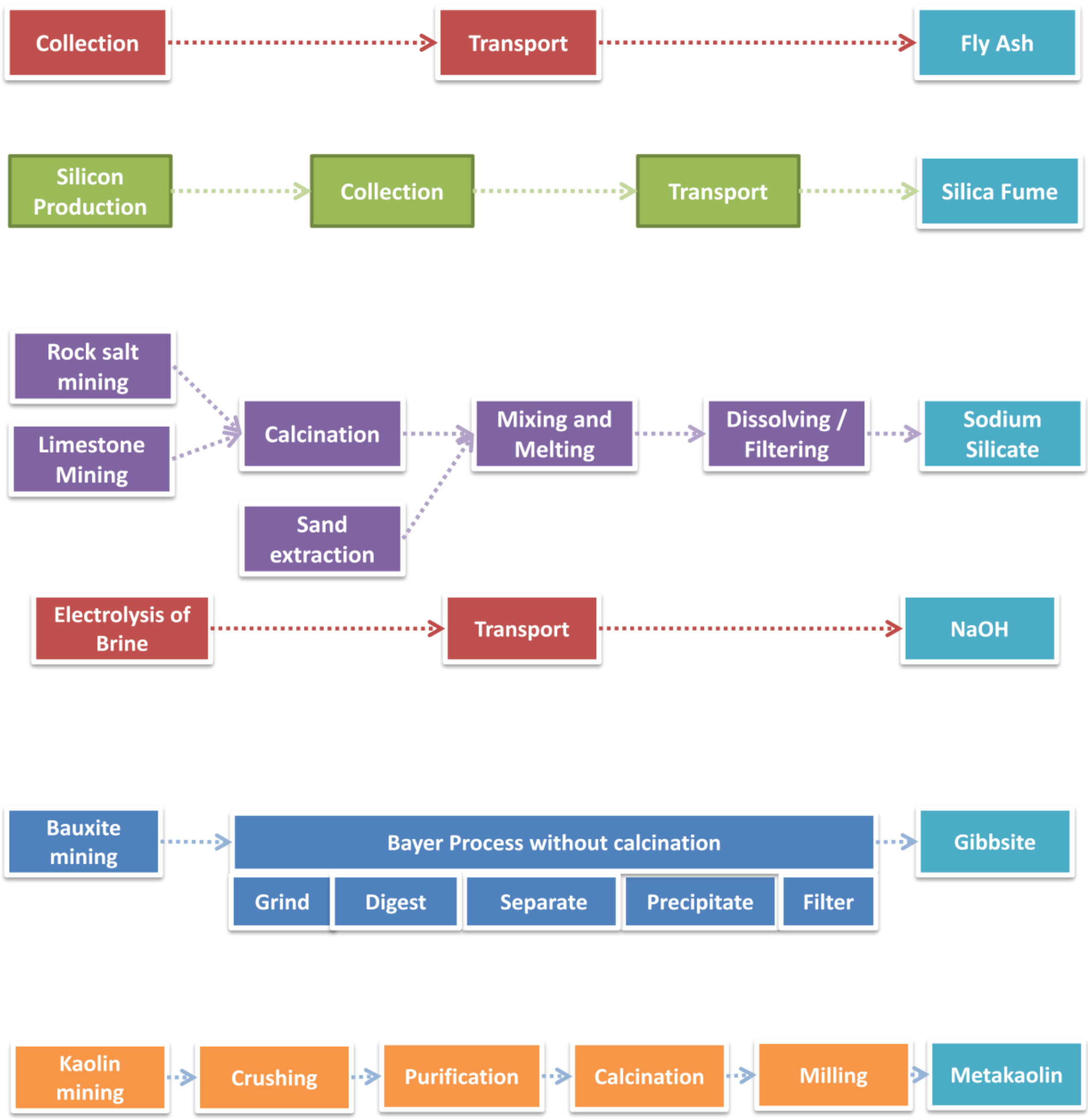

Collection
Transport
Fly Ash
Silicon Production
Collection
Transport
Silica Fume
Rock salt mining
Limestone Mining
Calcination
Sand extraction
Mixing and Melting
Dissolving / Filtering
Sodium Silicate
Electrolysis of Brine
Transport
NaOH
Bauxite mining
Bayer Process without calcination
Grind
Digest
Separate
Precipitate
Filter
Gibbsite
Kaolin mining
Crushing
Purification
Calcination
Milling
Metakaolin

Figure 3: Schematic of production of OPC-based concrete

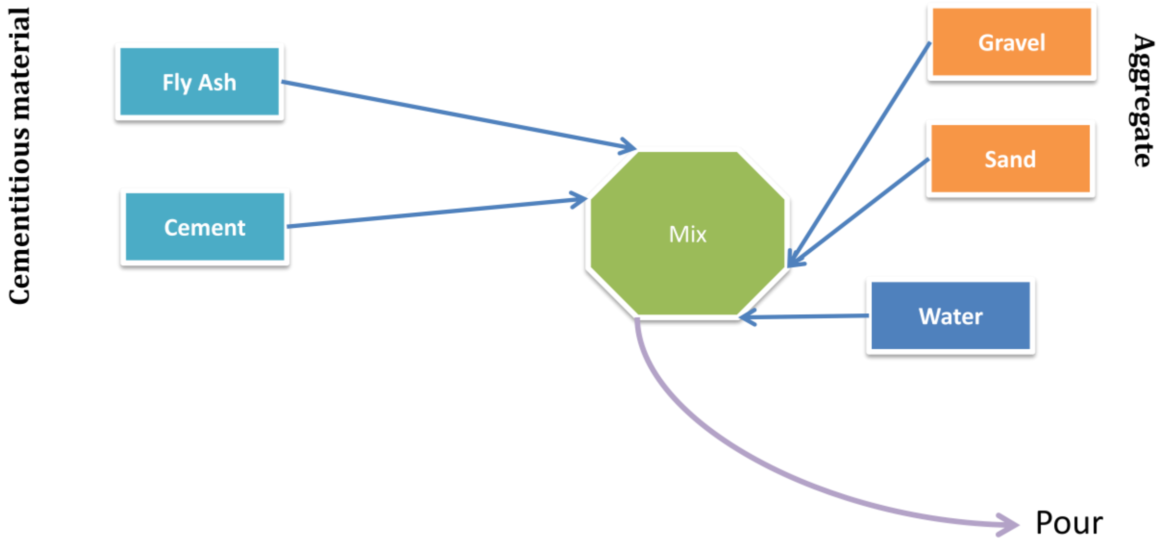


Figure 4: Life cycle production stages for OPC

The inventories of emissions, costs and energy usage were developed through a literature review of reported values and some theoretical estimates where no data was available. Attempts have been made to ensure that the data are used on a comparable basis, so that there is not a distortion of the boundaries of the analysis. Importantly, waste products (i.e. fly ash and silica fume[2]) are not allocated any of the emissions from the processes that produce them as a waste stream. The justification for this approach is that these wastes would not be generated without the production of their associated commercial product (e.g. electricity in the case of fly ash and silicon in the case of silica fume), and hence the emissions should be allocated to their respective commercial products. This assumption means that, apart from any post-collection processing, these materials come with no "embodied impacts".

Energy data have been obtained from the available literature – mostly this has been available as electricity and fuel or thermal energy usage. The energy usage has been vital to calculating the potential greenhouse gas emissions. Typically a high, average and low value have been available from the literature. Metakaolin was the most difficult material to develop an inventory for, as little if any verifiable life cycle data are available [22]. In lieu of this lack of data, the authors estimated energy and emissions values of the mining of

[2] There is some debate as to whether silica fume should be allocated some of the impacts of the production of silicon (from which it is a by-product / waste), due to the large scale usage in the cement industry. The argument against any allocation is that the silicon production process is not run or optimised for the production of silica fume. Silica fume is merely a profitable waste product. If environmental impacts are allocated to the waste stream, the use in cement is less attractive.

metakaolin based on energy for bauxite mining and the thermal energy for calcining metakaolin. These thermal energy estimates were calculated for heating kaolin from room temperature to 700^{o}C, assuming evaporation of all water formed by de-hydrolysis at a heat transfer and fuel utilisation efficiency of 65%.

Transportation of materials at all life cycle stages leading up to the production of the binder is of key importance, as the cost and emissions metrics (especially for waste products) can be highly affected by the distance and mode of transport [11, 21]. The transportation stages have been separated from the data gathered (wherever possible and appropriate), and transportation has been modelled separately. The transportation emissions [25-27] and cost data [28] are for typical Australian applications, with average distances calculated for feedstock delivery to the major centres of Adelaide, Brisbane, Melbourne, Perth or Sydney (all large users of concrete).

Transport distances were calculated for the most direct route from the typical source locations to the major centres, using a "great circle" calculation from the respective latitudes and longitudes (see Tables 1 and 2). The domestic locations for feedstock sources and OPC production and import are shown in Figures 5 and 6. The authors recognised that under some conditions, for example, the longer sea routes, the transportation path might be less direct. For land routes, a comparison using Google™ Maps and direct measurements reported by mining companies has indicated that the typical tortuosities would imply a distance typically 5 – 50% greater than the great circle distance. Typically, the shorter the distance is the less direct the route and therefore the higher the percentage error. This variability is incorporated in a sensitivity analysis for transport effect on the cost and carbon impacts. For a known location and feedstock source, an accurate distance should be used to obtain a specific comparison. It should be noted at this point that the costs presented here are in Australian dollars, and representative as of July, 2009.

Some feedstocks are reported in weight percentage of reactive material, while the actual form of the feedstock is a solution (e.g. – 50 wt% solution of NaOH and 37 – 40 wt% solution of sodium silicate). This does not affect the production impacts of the feedstock, however the extra mass of water has to be taken into account in the calculation of transport costs and emissions. While water content in feedstocks is acknowledged due to its impact on volume and therefore transport costs, the water added to the final geopolymer or OPC binder is not included at this stage, as it is assumed to be added at the site of use and quantification of associated transport is beyond the scope of this study. Water usage is another sustainability metric that should be included for further research, along with the embodied energy and emissions for the delivery of that water.

The OPC production flowsheet presented in Figure 4 is simplified, and does not include the addition of minor components such as superplasticiser or supplementary cementitious materials (SCMs) such as fly ash or slag. In particular, SCMs are often included in current cement mixes, and can have a significant impact on reducing the energy and greenhouse gas emissions from such cements [11]. Typical Australian cement blends contain 15 – 30% SCMs, hence the emissions from OPC blended cements in Australia are in the range of 760 – 860 kg $CO_{2\text{-eq}}$ / t rather than the 1 t $CO_{2\text{-eq}}$/ t for pure OPC clinker.

Once the inventory data were accumulated, the data were analysed in two ways. Firstly, the amount of each feedstock that would be equivalent to the entire inventory of greenhouse gases or cost for one tonne of OPC was calculated (refer to Figure 8). This value is useful as a guide to show that there is a limit to the amount of each feedstock which can be used before the budget, corresponding to one tonne of OPC, is depleted. (However, if one feedstock uses up the budget, the emissions from other feedstocks would have to be zero to keep the overall emissions equal to that for one tonne of OPC,) Secondly, some sample mixes of geopolymers which have been found to provide useable pastes were utilised as a case study (Figure 9) to examine whether the claims of significant greenhouse emissions reductions and potential cost parity in comparison with OPC are valid.

Table 1: Geopolymer feedstock and OPC transport and emissions data and references

Material	Classification	Specifications	Source Location	Life Cycle Steps Considered	Key References
Fly ash	Waste		Australia (coal-fired electricity generators)	Collection / Separation from flue gases;	[29-31]
Slag	Waste	Granulated;	Australia (steel-making facilities)	Wet cooling; granulation;	[32]
Sodium hydroxide (NaOH)	Product	50 wt% solution NaOH	Europe, USA, Japan, Saudi Arabia	Electrolysis of brine;	[33, 34]
Gibbsite (Uncalcined alumina)	Product		Australia (Alumina refineries)	Mining; Beneficiation; Bayer process (without calcination);	[34-38]
Sodium silicate	Product	37 wt% solution	Western Australia, China, India, UAE	Soda ash production / Sand mining; Furnace liquor production;	[22, 36, 39]
Metakaolin	Product		UK, USA, China	Mining; Beneficiation; Calcination;	[19, 22, 34, 40]
Silica fume	Waste / By-product		Western Australia, China, India	Collection;	[31, 40, 41]
OPC	Product		Australia	Mining; Grinding; Calcination; Re-grinding;	[6, 11, 14, 17, 18, 42-46]

Table 2: Transport distances – mean of values calculated to Adelaide, Brisbane, Melbourne, Sydney and Perth

	Distance (km)[a]					
Material	**Minimum**		**Average**		**Maximum**	
Fly ash	* 129	Average within own State;	1,408	Average across all coal-fired power stations in Australia;	3,015	Average to furthest coal-fired power station in Australia;
Slag	736	Average minimum for Australia;	* 1,186	Average for Australia;	1,629	Average to furthest steel-making facility;
NaOH	7,799	Sea transport;	* 12,258	Sea transport;	16,114	Sea transport;
Gibbsite	* 995	Average minimum for Australia; Rail transport;	2,225	Average for Australia; Road transport – articulated trucks;	3,201	Average minimum for Australia; Road transport – rigid trucks;
Sodium silicate	2,142	Average minimum for Australia from domestic sources; Rail transport;	* 7,549	Sea transport;	2,142 (11,162)	Road transport – rigid trucks; (Sea transport;)
Metakaolin	7,589	Sea transport;	* 12,367	Sea transport;	16,625	Sea transport;
Silica fume	2,475	Average minimum for Australia from domestic sources; Rail transport;	* 6,567	Sea transport;	9,458	Sea transport;
OPC[b]	13	Average minimum within own State; Road transport – articulated trucks;	* 84	Average within own State; Road transport – articulated trucks;	274	Average maximum within own State; Road transport – rigid trucks;

[a] Maximum distances and mode of transport are selected as those which maximise CO_2 emissions; * values assumed to be "typical" for Australia

[b] Imports of cement to Australia have been growing in recent years and may contribute 10-20% of the market however, they are not included in this assessment.

Figure 5: Map of domestic feedstock sources and end use destinations

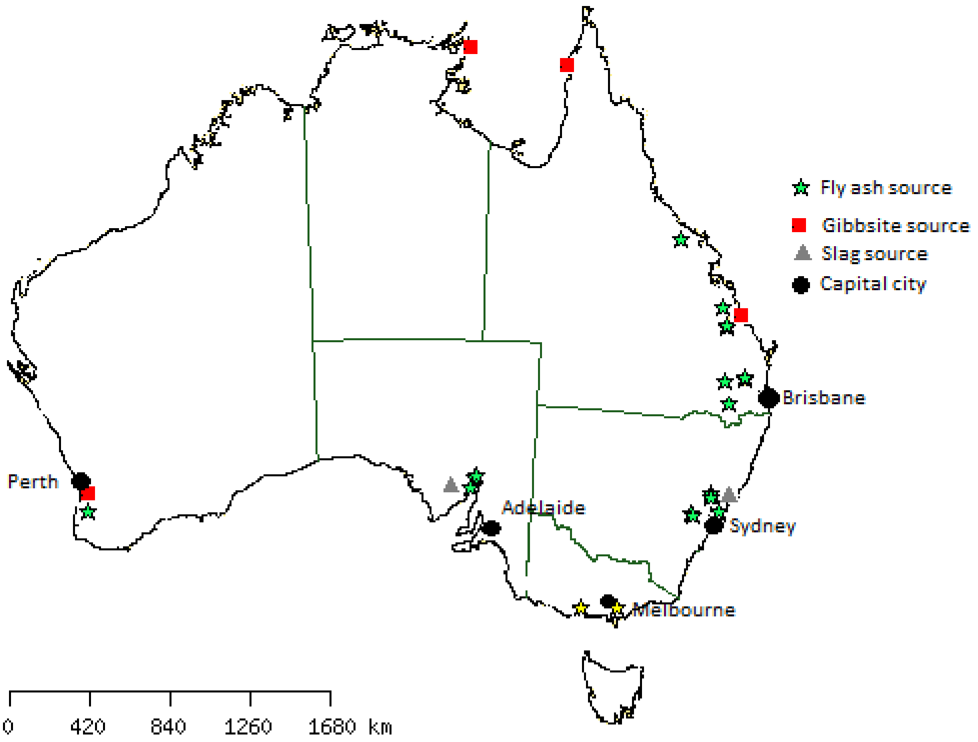
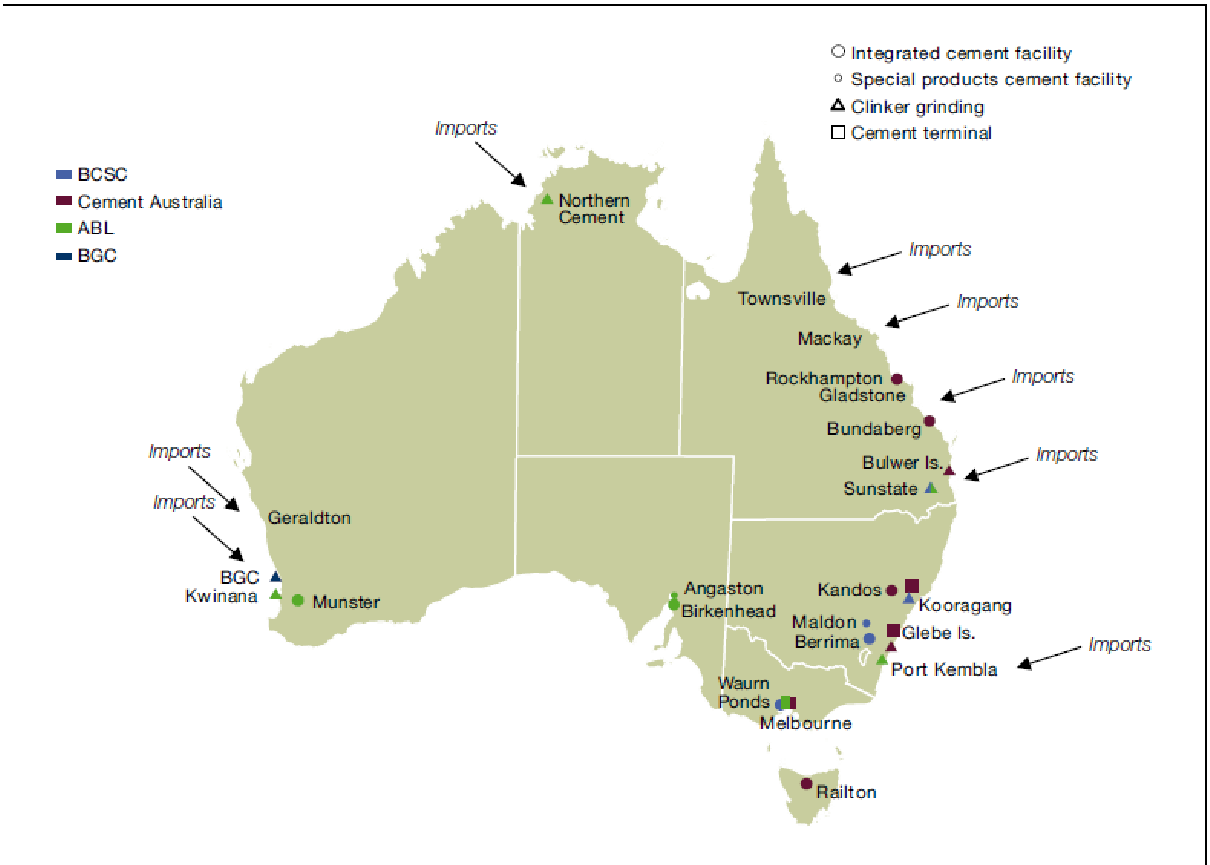


Figure 6: Map of OPC cement production and import centres [48]



3. RESULTS

The key results from the study are presented in Figures 7 to 9. Figure 7 shows the estimated values of performance metrics (fuel, electricity and greenhouse gas emissions) for each of the geopolymer feedstocks. The grey bars indicate the estimated average value for Australian conditions. The average is not based on a weighted mean, which would be desirable, but is the value judged to most closely approximate the Australian average, given the potential sources of feedstock and location of usage. In actual fact, many of the geopolymer feedstocks would be sourced from as close as possible to keep transport cost down and thus the metric values are more likely to be closer to the minimums. Likewise, the OPC market is highly competitive, hence the sources of OPC would typically be those closest to the end user in order to reduce transportation costs (although there is emerging competition with imported cement that will effect this [45, 46]). The error bars indicate the range of values found in the literature.

Figure 7: Geopolymer feedstock production metrics - error bars indicate the range of values found in the literature (NaOH and sodium silicate figures quoted here are on the basis of 1t of NaOH or sodium silicate solid, although the actual supply will most likely be as a solution. For sodium silicate we have used a SiO_2 : Na_2O weight ratio of 2.0.)

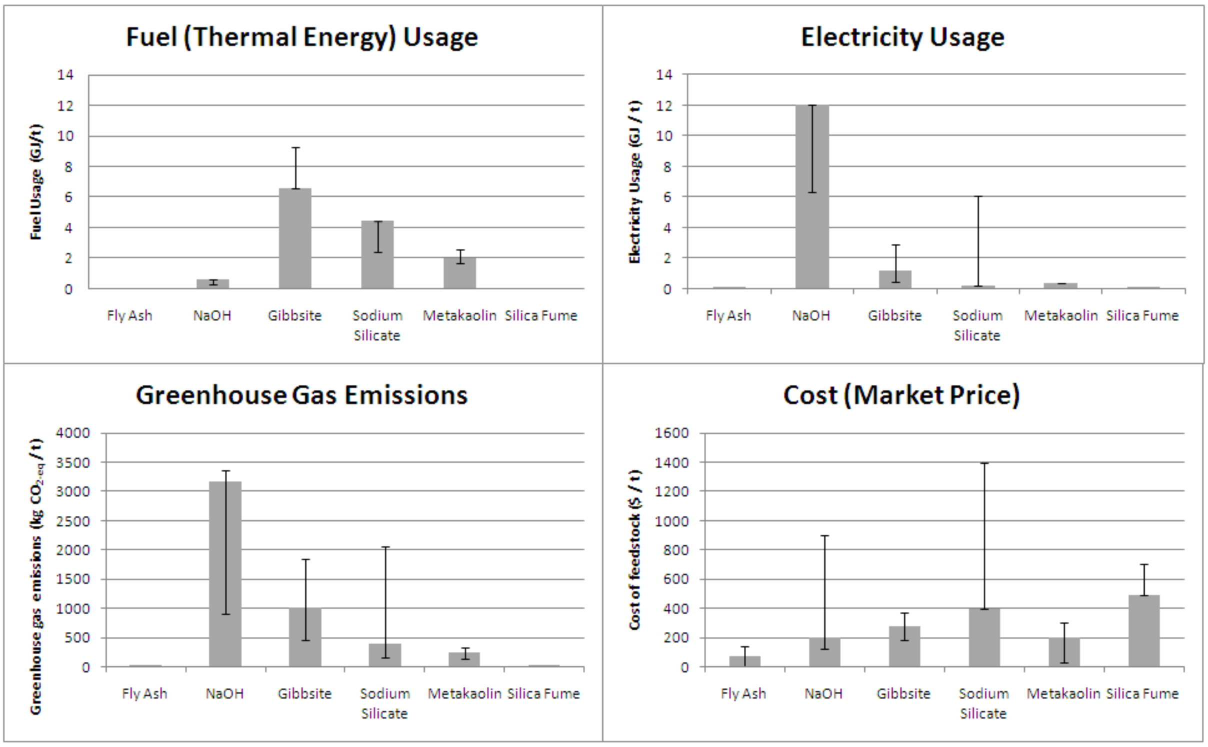


Figure 8 gives estimates of the how much a particular feedstock could be used before the resulting geopolymer would have an equal greenhouse gas emissions or cost impact to that of OPC. This figure can be taken as the absolute limit for a given feedstock in producing the equivalent geopolymer to replace one tonne of OPC. The data are presented on the basis of production alone and production plus transportation. The results indicate that the cost limitations – especially with the cost of transportation included – are likely to be the limiting factor in geopolymer performance comparison. However, in the situation where a carbon tax of \$20 / t $CO_{2\text{-eq}}$ is applied, most geopolymer feedstocks become cost competitive.

Figure 8: Geopolymer feedstock limitations on amount that can be added for an equivalent 1 tonne OPC on the basis of cost or $CO_{2\text{-eq}}$- error bars indicate the range of values found in the literature

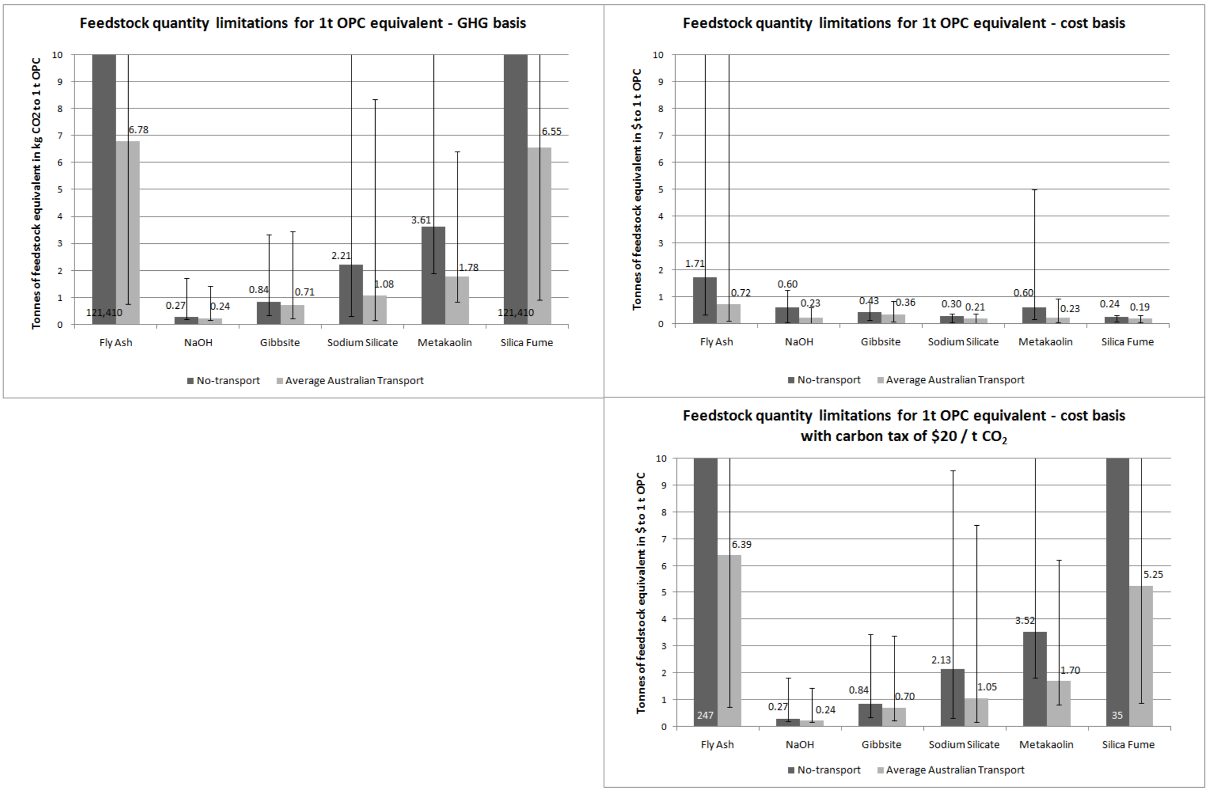


Figure 9 shows a comparison between 4 potential geopolymer mixes (see Table 3 for mix details) on a production basis alone and a production plus transportation basis. This indicates that geopolymers can range in potential cost and greenhouse gas competitiveness from much lower (approximately 72% reduction in cost and 97% reduction in greenhouse emissions) to the same or higher than an OPC mixture (up to approximately eight-fold cost increase and 14% increase in greenhouse emissions). On a production-only basis, the geopolymer is seen to be significantly better in greenhouse emissions terms, and potentially competitive on a cost basis. However, when transportation is included the benefits are less clear – for short distances there is a definite benefit but for long distances there is a negative impact.

Figure 9: Example mixes - comparison of greenhouse gas emissions and cost on a dry tonne basis (Comparison of feedstock production only and feedstock production with transport included (designated "–transport") emissions and costs)

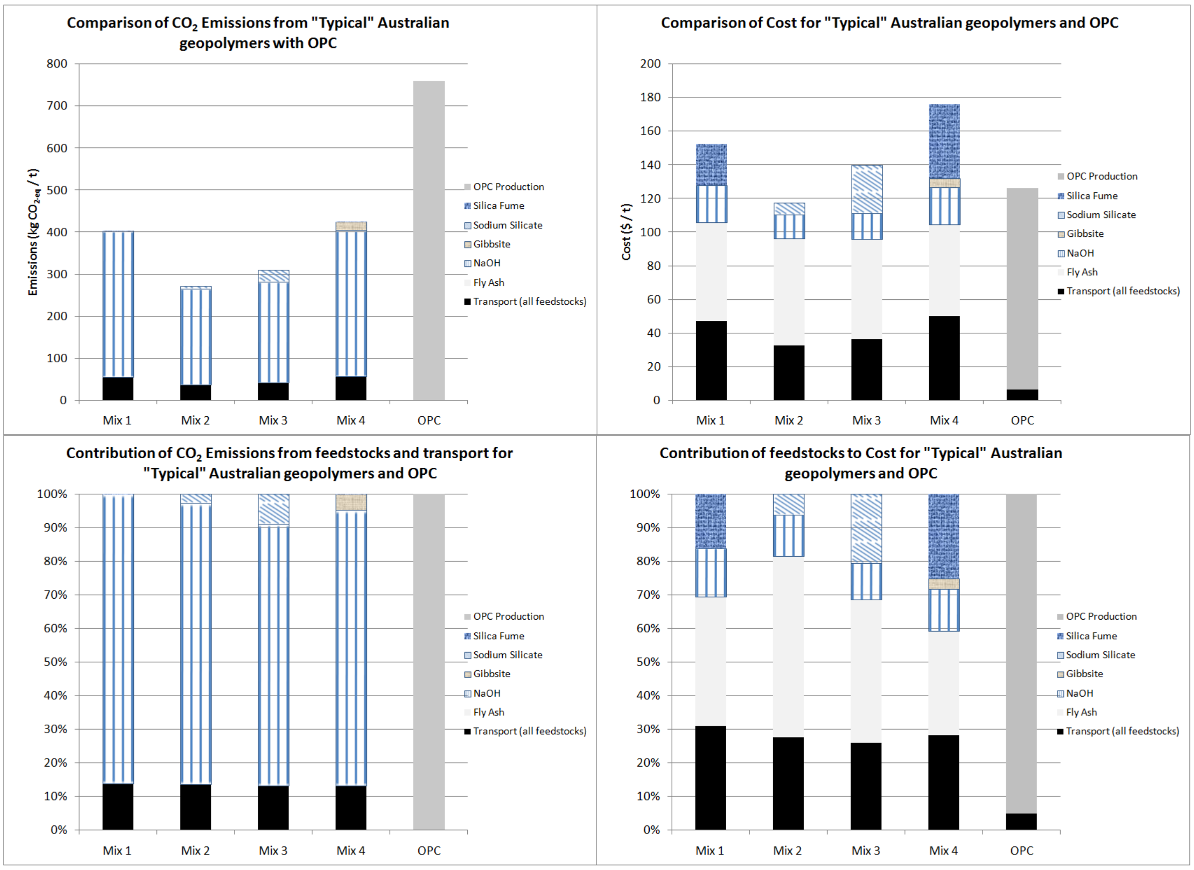


Table 3: Example geopolymer paste mixes (wt % without added water)[3]

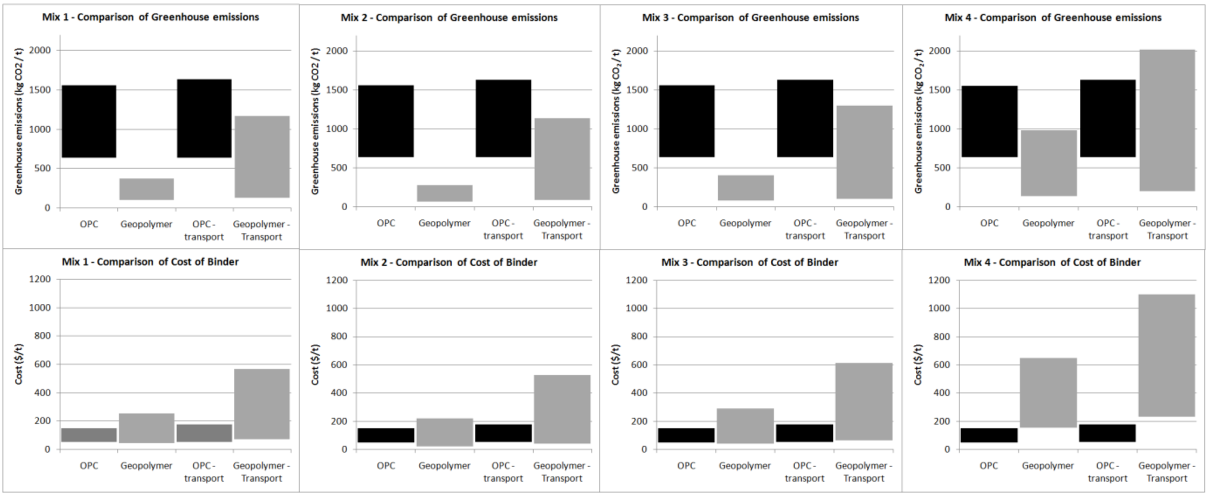
	Mix 1	Mix 2	Mix 3	Mix 4
Fly ash	84	91	85.2	78
NaOH	11	7.2	7.6	11
Sodium silicate	0	1.8	7.2	0
Silica fume	5	0	0	9
Gibbsite	0	0	0	2

Given the variability in the emissions and costs for geopolymers produced from feedstocks in Australia, it was thought to be important to find a typical value of the emissions and cost. This typical value could then be used as a 'first guess' estimate for comparison with OPC products. Based on an understanding of the various feedstock production drivers, it was determined that the transportation distances to find the "typical" value in an Australian context would be the minimum value for fly ash, sodium silicate, gibbsite and silica fume, and the average value for NaOH and metakaolin. The values for greenhouse gas and cost that

[3] The four mixes shown in this table are commonly used mixes with various fly ashes with a strength of approximately 40 MPa, made with a range of starting materials to provide a indication of range of cost and carbon dioxide emissions.

would be expected for the "typical" geopolymers using the above four mixes are shown in Table 4. These typical values and the corresponding equivalent for OPC are also shown in Figure 10, as well as the contribution that the production of each feedstock and transport make to the overall cost and emissions. This analysis shows that geopolymers from typical feedstock sources, typically in close proximity to the point of usage, could produce improvements of up to 64% in terms of greenhouse gas emissions over OPC. In cost terms, the performance of geopolymers showed that an improvement over OPC is possible, with costs ranging from 7% lower to 39% higher than OPC. This indicates that geopolymers are likely to be disadvantaged on price performance under current pricing structures and without a carbon price. Figure 10 further indicates that the key source of emissions for the geopolymer mixes examined here is caustic soda. Thus one of the important research questions for geopolymer development to improve the greenhouse impacts of their product even further must be how to reduce the dependence on raw caustic soda production, or to source this feedstock from lower-emitting producers.

Figure 10: Comparison of contributions to a "typical" Australian geopolymer paste and OPC



To illustrate the method of calculation:

$$GHG_{Total} = \sum_{i=1}^{n} m_i \left(d_i e_i + p_i\right)$$

Where:

GHG_{Total} = total greenhouse gas emissions

m_i = mass of component i

d_i = distance transported (by a given mode of transport)

e_i = emissions factor for transportation mode

p_i = emissions per unit mass of i produced

For the typical Australian situation this could be expressed as:

$$GHG_{Total} = m_{fa}\left(0.09d_{fa} + 0.007\right) + m_{slag}\left(0.09d_{slag} + 0.027\right) + 2m_{NaOH}\left(0.02d_{NaOH} + \frac{3165}{2}\right)$$

$$+ m_g\left(0.01d_g + 1017\right) + \frac{m_{NaSi}}{0.37}\left(0.02d_{NaSi} + 386 \times 0.37\right) + m_m\left(0.02d_m + 236\right) + m_{SiFume}\left(0.02d_{SiFume} + 0.007\right)$$

Where the subscripts denote:

fa = fly ash;

NaSi = sodium silicate;

g = gibbsite;

m = metakaolin;

SiFume = silica fume;

Also, it must be noted that this equation includes adjustments to convert from dry weight to total solution weight for sodium silicate and sodium hydroxide.

Table 4: Typical greenhouse gas emissions and costs for four geopolymer mixes compared with OPC

	Mix 1	Mix 2	Mix 3	Mix 4
GP CO2-eq (kg / t binder)	404	271	310	425
Blended OPC CO2-eq (kg / t binder)	760			
Difference	47%	64%	59%	44%
Cost ($ / t binder)	152	118	140	176
OPC Cost ($ / t binder)	120			
Difference	-21%	7%	-11%	-39%

Literature mixes for geopolymers and comparative OPC concretes were examined and the carbon and cost factors from this research applied. It was identified that:

1. A comparable amount of cement or geopolymer paste is used to make concrete (both in kg / m^3 of concrete and in wt %)
2. The carbon and cost contributions of aggregate were minimal and comparable (due to the first point), and typically made little difference to the comparative impact over a comparison of the binders
3. The amount of water used in the mixtures was typically lower for geopolymers

The data obtained for these comparisons are shown in Table 5. The impact of transport for these mixes is in the range of 5 – 21% of the total CO_2 emissions for OPC concrete and 41 – 43% for geopolymer concrete, which is indicative of the much longer distances travelled by geopolymer feedstocks. When only the binder was considered, the impact of transport fell to

1 – 10% for OPC versus 40 – 45% for geopolymer paste, which shows the relative impact of transporting aggregate and other feedstocks. A simple sensitivity analysis of the effect of transport inaccuracies on overall emissions is shown in Table 6. While geopolymers will be affected to a greater extent than OPC concretes (due to the higher transport contribution to feedstock impacts), the distances for geopolymers are significantly longer, and therefore likely to be more accurate than the distances for OPC for the analysis in this paper. This work has not included consideration of the 10-20% of imported cement that has recently become a part of the Australian market [45, 46] however, the additional transport involved in importing cement will only add to the greenhouse gas reduction argument for geopolymers.

Table 5: Calculations on reference geopolymer and OPC concrete mixes

	Mass of Component (kg / m^3)									
	Weil (2009) [21]		Stengel (2009) [23]		Prusinski (2006) [10] (OPC Concrete)				Sumajouw (2009) [47] (Geopolymer)	
Component	**Cement concrete**	**Geopolymer**	**Cement concrete**	**Geopolymer**	**1**	**2**	**3**	**4**	**1**	**2**
Cement	340		240		360	234	180	288		
slag		230				87	124			
fly ash		57	120	408				44	408	404
reactive waste		83								
Na silicate (37%)		33		103					103	102
NaOH (50%)		24		41					41	41
de-ionised water	170	99	160	22.5	141	141	141	141	26	16.5
Superplasticizer			6	6					6	6
Gravel	1878	1878	1150	1294	1127	1127	1127	1127	1202	1190
Sand			750	554	831	831	831	831	647	640
Concrete mass (kg / m^3)	2388	2404	2426	2428.5	2459	2420	2403	2431	2433	2400
Binder mass (kg / m^3)	510	526	526	580.5	501	462	445	473	584	569.5
wt % binder	21.4	21.9	21.7	23.9	20.4	19.1	18.5	19.5	24.0	23.7
Dry binder wt%	14.2	16.4	15.1	19.9	14.6	13.3	12.7	13.7	19.9	20.1
SCM % of total CM	-	100.00	33.33	100.00	-	27.10	40.79	13.25	100.00	100.00
Water mass (kg / m^3)[4]	170	131.79	160	98.22	141	141	141	141	99.567	88.278
wt% water	7.1	5.5	6.6	4.0	5.7	5.8	5.9	5.8	4.1	3.7
Aggregate (kg / m^3)	1878	1878	1900	1848	1958	1958	1958	1958	1849	1830
wt % aggregate	78.6	78.1	78.3	76.1	79.6	80.9	81.5	80.5	76.0	76.3
Metrics (Feedstock only)										
kg CO_{2-eq} / m^3	316	115	237	200	341	233	187	279	201	200
kg CO_{2-eq} for binder	290	89	205	170	307	199	153	245	170	169
Cost of binder ($ / m^3)	41	44	37	78	43	34	30	38	78	77
Metrics (With transport)										
kg CO_{2-eq} / m^3	333	201	284	339	376	279	237	320	342	340
kg CO_{2-eq} for binder	292	161	222	283	310	212	170	253	283	282
Cost of binder ($ / m^3)	43	98	51	157	45	45	45	44	157	156

[4] Water mass includes all added water in reagent solutions and mixing water.

Table 6: Sensitivity of emissions to transport distance underestimation

	Relative increase in emissions	
	Geopolymer concrete	OPC concrete
5 % increase in transport distance	~2%	<1%
50% increase in transport distance	~20%	3 – 10%

4. DISCUSSION

The results of this study indicate that it is not possible to make a simple sustainability comparison on the use of OPC and geopolymers. This is due to the significant impact of reagent transport and variability in the source of energy and technology used to produce the reagents. Transport has been minimised for OPC, as it is an established product; however, geopolymers are yet to go through this cycle of scale-up. Large scale geopolymer use is likely to lead to lower costs due to large orders of reagents. Even so, there seems to be significant potential for geopolymers to be cost effective and environmentally beneficial.

This work has taken a broad approach, and the availability of better quality data would produce a more accurate analysis of the impacts – especially in relation to metakaolin production. It is also important that research be undertaken to develop greater understanding of how geopolymer performance in various applications will affect the environmental and cost inventories. If the lifetime and recyclability are included, the results of the current study may vary extensively. Further work should also be done to incorporate further sustainability metrics, and give a wider picture of sustainability performance.

This work has brought together a range of reported data from the literature, in order to demonstrate the potential variability in the sustainability potential of geopolymers compared with OPC. The results show that it is important to assess the specific source of OPC and geopolymer feedstocks and transport impacts in order to be able to definitively state the relative sustainability performance for a given application in a given location. This work will be facilitated to some degree by a geopolymer calculator that is currently under development by the co-authors from Curtin University of Technology. There is also potential for optimisation and mapping to give an indication of the regions of applicability for most benefit from geopolymers from given feedstocks.

The values for improved greenhouse gas emissions for geopolymer pastes compared to OPC are in the mid-range of estimates for geopolymer concrete as reported by other authors [21, 23]. However, this study acknowledges that there is a significant potential for variability, depending on the particular mix formulation and source of feedstocks.

The examination of concrete mixes for OPC and geopolymer concretes has indicated that the impact of transport is higher in geopolymer concretes. Comparison of geopolymer paste versus OPC is found to be sufficiently valid and reasonable given the similar amount of geopolymer binder or cement used to create a cubic metre of concrete.

Key challenges for geopolymer development will include the need to reduce cost by utilising (for example) less expensive waste feedstocks, and by optimising the amount of transport required to obtain those feedstocks at the point of use. Optimisation of transport is of particular concern in a vast, relatively isolated country such as Australia. Geopolymers' advantage on a carbon basis may increase with the optimisation of feedstock transport and the increasing reliance on imported cement [45, 46]. Additionally, there is further potential to reduce greenhouse gas emissions through reducing transport distances and reducing the dependence on high-emissions raw caustic soda for geopolymer pastes.

5. CONCLUSIONS

This paper indicates that there is great potential for geopolymers to reduce the climate change impacts of cement production. For the proposed "typical" Australian geopolymer product, there is an estimated 44-64% improvement in greenhouse gas emissions over OPC, while the cost of these geopolymers can be up to twice as high as OPC. However, the paper also indicates that those benefits are only realisable given the most appropriate source of feedstock and the least cost transportation. The broad range of potential feedstock sources leads to a very wide range of potential impacts: compared with emissions from OPC concrete, emissions from geopolymer concrete can be 97% lower up to 14% higher. Each application for geopolymers therefore needs to be assessed for its specific location, given that the impact of location on overall sustainability is one of the determining factors.

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