## Green House Gas Emissions

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# Green House Gas Emissions due to Concrete Manufacture*

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**Abstract**

**Background, Aim and Scope.** The issues of environmental impacts of concrete have become important since many major infrastructure owners are now requiring environmentally sustainable design (ESD). The carbon dioxide ($CO_2$) emissions are often used as a rating tool to compare the environmental impact of different construction materials in ESD. Currently, the designers are forced to make estimates of $CO_2$ emissions for concrete in ESD based on conjecture rather than data. The aim of this study was to provide hard data collected from a number of quarries and concrete manufacturing plants so that accurate estimates can be made for concretes in ESD.

**Materials and Methods.** This paper presents the results of a research project aimed to quantify the $CO_2$ emissions associated with the manufacture and placement of concrete. The life cycle inventory data was collected from two coarse aggregates quarries, one fine aggregates quarry, six concrete batching plants and several other sources. The results are presented in terms of equivalent $CO_2$ emissions. The potential of fly ash and ground granulated blast furnace slag (GGBFS) to reduce the emissions due to concrete was investigated. A case study of a building is also presented.

**Results.** Portland cement was found to be the primary source of $CO_2$ emissions generated by typical commercially produced concrete mixes, being responsible for 74% to 81% of total $CO_2$ emissions. The next major source of $CO_2$ emissions in concrete was found to be coarse aggregates, being responsible for 13% to 20% of total $CO_2$ emissions. The majority contribution of $CO_2$ emissions in coarse aggregates production was found to from electricity, typically about 80%. Blasting, excavation, hauling and transport comprise less than 25%. While the explosives had very high emission factors per unit mass, they contribute very small amounts (<0.25%) to coarse aggregate production, since only small quantities are used. Production of a tonne of fine aggregates was found to generate 30% to 40% of the emissions generated by the production of a tonne of coarse aggregates. Fine aggregates generate less equivalent $CO_2$ since they are only graded, not crushed. Diesel and electricity were found to contribute almost equally to the $CO_2$ emissions due to fine aggregates production. Emission contributions due to admixtures were found to be negligible. Concrete batching, transport and placement activities were all found to contribute very small amounts of $CO_2$ to total concrete emissions.

**Discussion.** The $CO_2$ emissions generated by typical normal strength concrete mixes using Portland cement as the only binder were found to range between 0.29 and 0.32 t $CO_2$-e/m$^3$. GGBFS was found to be capable of reducing concrete $CO_2$ emissions by 22% in typical concrete mixes. Fly ash was found to be capable of reducing concrete $CO_2$ emissions by 13% to 15% in typical concrete mixes.

**Conclusions.** The results presented are based on typical concrete manufacturing and placement methods in Australia. The data presented in this paper can be utilized to compare green house gas emissions due to concrete with those associated with alternative construction materials.

**Recommendations and Perspectives.** The various rating schemes used to compare alternative construction materials should use models such as the one presented in this paper, based on hard data so that reliable comparisons can be made. A case study is presented in this paper demonstrating how the results may be utilized.

**Keywords:** Carbon dioxide emissions; concrete; fly ash; granulated blast-furnace slag; life cycle assessment (LCA); Portland cement

## Introduction

Concrete is the most widely used construction material. Current average consumption of concrete is about 1 tonne per year per every living human being. Human beings do not consume any other material in such tremendous quantities except for water. Due to its large consumption, even small reductions of green house gas emissions per ton of manufactured concrete can make a significant global impact. This paper presents a systematic approach to estimate carbon dioxide ($CO_2$) emissions due to the various components of concrete manufacture. Reliable estimates of green house gas emission footprint of various construction materials are becoming important, because of the environmental awareness of the users of construction material. Life cycle assessment of competing construction materials (e.g. steel and concrete) [1] can be conducted before the type of material is chosen for a particular construction. This paper provides green house gas emissions data collected from typical concrete manufacturing plants for this purpose.

The basic constituents of concrete are cement, water, coarse aggregates and fine aggregates. Extraction of aggregates has

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considerable land use implications [2]. However, the major contributor of green house emissions in the manufacture of concrete is the Portland cement. It has been reported that the cement industry is responsible for 5% of global anthropogenic $CO_2$ emissions [3]. As a result, emissions due to Portland cement have often become the focus when assessing the green house gas emissions of concrete. However, as demonstrated by the data presented in this paper, there are also other components of concrete manufacture which are responsible for green house gas emissions that need consideration. With users beginning to require detailed estimates of the environmental impacts of the materials in new construction projects, this study was intended to provide the basis for a rating tool for concrete, based on $CO_2$ emissions.

Other cementitious components considered include ground granulated blast furnace slag (GGBFS), a by-product of the steel industry, and fly ash, a by-product of burning coal. These two materials are generally used to replace a portion of the cement in a concrete mix. The use of water in concrete leads to minimal $CO_2$ emissions, which leaves cement, coarse and fine aggregates, GGBFS and fly ash as the main material contributors to the environmental impacts of concrete. In addition to the production of materials, the processing components of concrete production and placement were considered. Transport, mixing, and in-situ placement of concrete all require energy input leading to $CO_2$ emissions. **Fig. 1** shows the system that was considered for this research.

The $CO_2$ emissions from most of the activities involved in concrete production and placement result from the energy consumed to accomplish them. Hence, to find the $CO_2$ emissions associated with an activity, the energy consumption per unit of material produced had to be audited. The exception to this rule is cement, where approximately 50% of the emissions are process based, due to the decomposition of limestone in the kiln with the remainder associated with kiln fuels and electricity [3,6]. Previous research into the environmental impacts of cement production has already yielded several estimates of the $CO_2$ emissions per tonne of cement produced. Similarly, fly ash and GGBFS have also both been investigated previously, and their emissions quantified. So the research that was conducted for this paper covered the production of coarse and fine aggregates and admixtures, raw materials transport, concrete batching and transport, and on-site placement activities.

## 1 Methodology

The procedures used to calculate $CO_2$ emissions due to various energy sources in this study were obtained from the Australian Greenhouse Office Factors and Methods Workbook [4]. **Table 1** below shows the emission factors that were

**Table 1:** Full fuel cycle $CO_2$ emission factors [4]

| Energy source | Emission factor | Unit |
|---|---|---|
| Diesel | 0.0030 | t $CO_2$-e/L |
| Electricity | 0.001392 | t $CO_2$-e/kWh |
| Riogel [a] | 0.1439 | t $CO_2$-e/tonne product |
| Bulk emulsion [b] | 0.1659 | t $CO_2$-e/tonne product |
| Heavy ANFO [c] | 0.1778 | t $CO_2$-e/tonne product |
| LPG [d] | 0.0018 | t $CO_2$-e/L |

[a, b, c]: explosives; [d]: liquefied petroleum fas

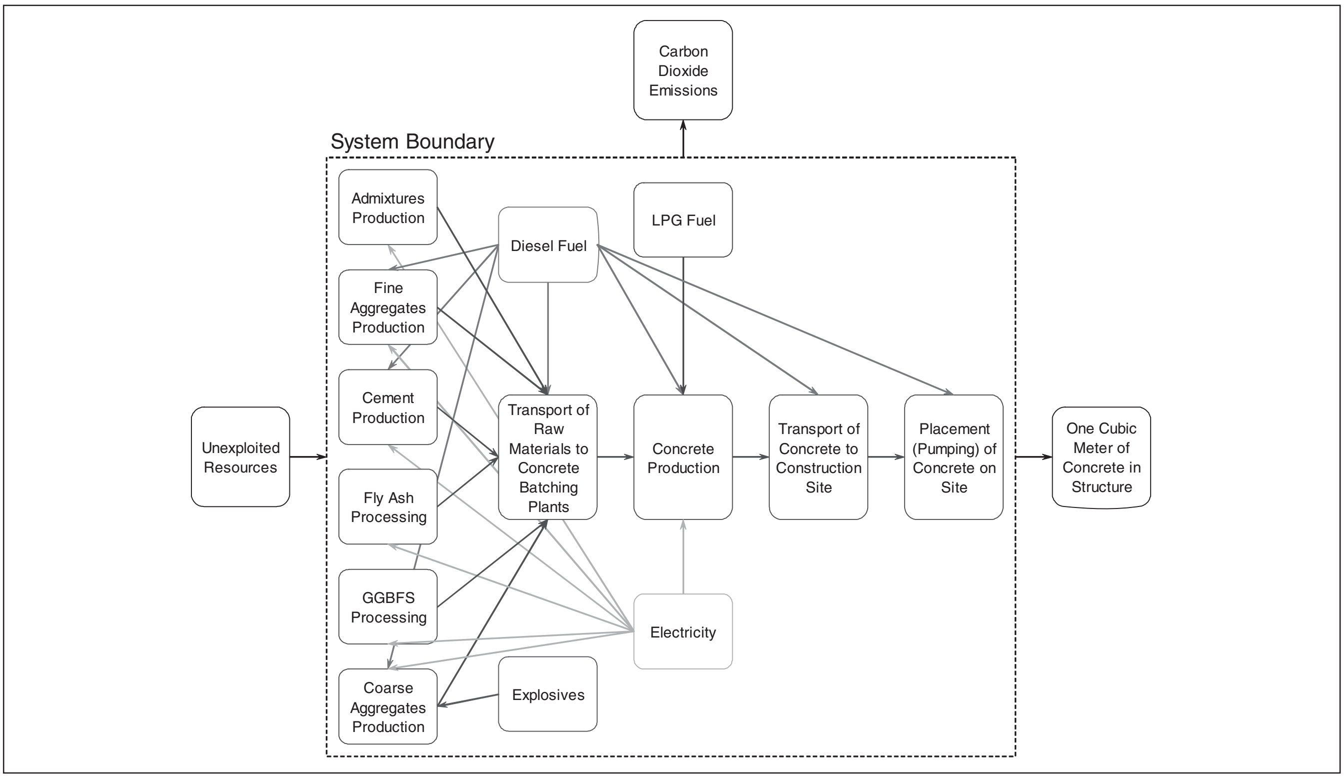


**Fig. 1:** Concrete $CO_2$ emissions system diagram

sourced from this publication. It should be noted that $CO_2$-e ($CO_2$ equivalents) are used as the unit, which is adjusted to include the global warming effects of any $CH_4$ or $N_2O$ emitted from the same fuel or process. These figures are appropriate for Melbourne, Australia, and may vary elsewhere around the world, due to differences in energy or fuel production methods. In 2004–2005 the electricity mix in Melbourne was generated from brown coal (91.3%), oil (1.3%), gas (5.4%), hydro (1.4%), wind (0.5%) and biogas (0.1%) [5].

## 2 Emissions due to Coarse Aggregates

Data to estimate the $CO_2$ emissions due to the production of coarse aggregates was gathered from two quarries. The first produced granite and hornfels aggregates, and the second produced basalt aggregates. Note that the two quarries that were chosen for analysis were considered to be typical examples. The production of both these types of coarse aggregates commences with the use of explosives to blast the rock from the quarry faces into medium size boulders and rocks. Diesel powered excavators and haulers then remove the rubble and dump it into electric crushing and screening equipment. Finally diesel powered haulers move the final graded products into stockpiles. As part of this study two coarse aggregates quarries (basalt and granite/hornfels) were audited for energy consumption and total productivity over a six-month period. This information was taken from fuel, electricity and explosives invoices, and site sales figures. The fuel, electricity and explosives data was used to calculate the amount of $CO_2$ produced per tonne of aggregate produced at each site. Using the emission factors presented in Table 1, $CO_2$ emissions per tonne of granite/hornfels was found to be 0.0459 t $CO_2$-e/tonne. $CO_2$ emissions per tonne of basalt was found to be 0.0357 t $CO_2$-e/tonne. These figures include the average contribution from transport from the quarry to the concrete batching plants. **Fig. 2** below shows the contribution of each energy source.

Electricity is responsible for the majority of $CO_2$ emissions for each type of aggregate. This labels the crushing process as the most significant part of the coarse aggregates production process from an environmental perspective. On-site blasting, excavation and hauling, in addition to off-site transport comprise less than 25% of the total emissions for coarse aggregates. It should be noted that while the explosives have very high emission factors, they contribute very small amounts (<0.25%) to the overall emissions, since such small quantities are used. To achieve significant environmental improvements in the production of aggregates, the crushing process needs to be targeted. Intelligent placement of explosives during the initial blasting process can reduce the demand on the electrical crushing equipment by blasting the rock into smaller fragments prior to crushing. Maintenance of crushing equipment is another way to lower electricity demands. Clearly the replacement of old, inefficient machinery will lead to lower energy demands.

## 3 Emissions due to Fine Aggregates

The fine aggregates investigated in this study begin as raw sand, which is strip-mined by excavators and loaded into haulers. The haulers dump the sand where it is washed into a pumpable slurry which is piped to the grading plant. Electric vibrating screens filter the sand into standard grades, which are then stockpiled. One fine aggregates quarry was audited for energy consumption and total productivity over a six-month period. The amount of $CO_2$ released during the production and subsequent transport of one tonne of concrete-sand was found to be 0.0139 t $CO_2$-e/tonne. This is 40% of the figure for basalt coarse aggregate, and 30% of the figure for granite coarse aggregate. The lack of a crushing step explains the difference between the emissions of fine and coarse aggregates. **Fig. 3** below shows the contribution of each energy source to the $CO_2$ emissions associated with fine aggregates.

Diesel and electricity contribute almost equally to the $CO_2$ emissions from the production and transport of fine aggregates. The diesel is nearly all consumed by the strip mining and on/off-site transport operations. The efficiency of these processes is largely dictated by the quality of the machinery being used. The replacement of ageing excavators and haulers will lead to greater fuel efficiency, and hence lower $CO_2$ emissions. Electricity is consumed by the pumping and grading equipment. The emissions associated with these processes

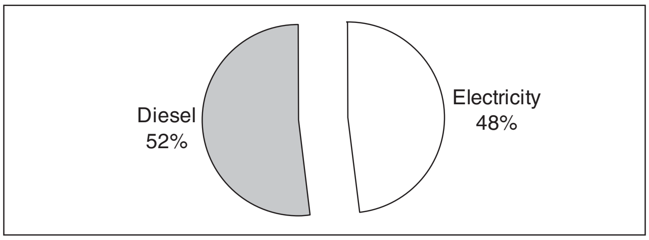


**Fig. 3:** Fine aggregates $CO_2$ emissions breakdown

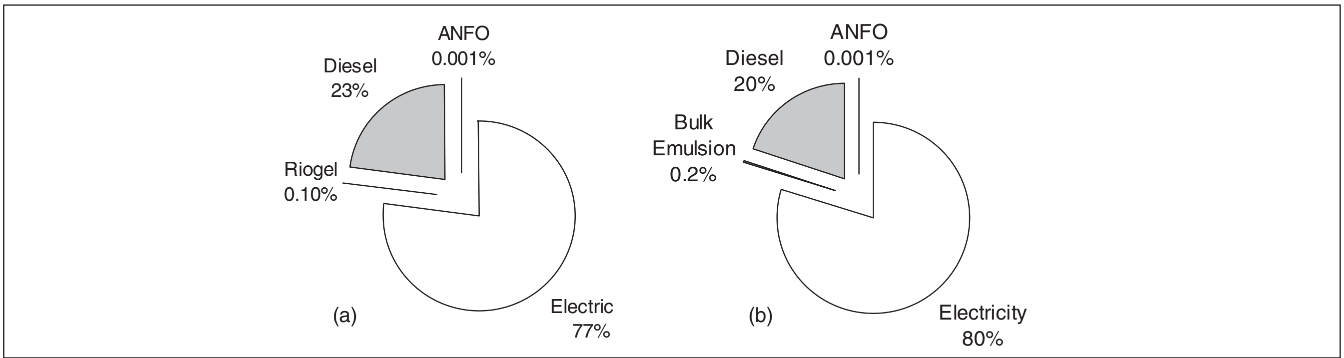


**Fig. 2:** (a) Basalt and (b) Granite/Hornfels $CO_2$ emissions breakdowns

are largely fixed. Savings could be made by periodically relocating the screening plant closer to the source of the slurry, but the emissions associated with moving the equipment would need to be assessed before this course of action was taken. In general, the sand mining process is fairly well established, and intentionally or otherwise, is already organised to generate minimal $CO_2$.

## 4 Emissions due to Cement, Fly Ash, GGBFS and Admixtures

The environmental impacts associated with cement production have been investigated thoroughly in recent times [3,6–9]. Decomposition of limestone is an essential process in Portland cement production which takes place in the cement kiln. The chemical reaction for this process is $CaCO_3 \rightarrow CaO + CO_2$. This process releases 0.5 ton of $CO_2$ for every ton of CaO produced. The high energy consumption of the kiln produces additional $CO_2$ emissions which are added to obtain the total emissions due to Portland cement manufacture. All of the figures for cement production in Australia lie around 0.8 t $CO_2$-e/tonne, which is within the range of the other figures from around the world, which vary from approximately 0.7 t $CO_2$-e/tonne to 1.0 t $CO_2$-e/tonne [3,10,11]. The most recent and extensively researched figure was found to be that presented by Heidrich et al. in 2005 [8], which was adopted for this project. The final emission factor that was used for cement in this project was 0.82 t $CO_2$-e/tonne, which includes transport of cement to concrete batching plants.

A part of the $CO_2$ emissions due to decomposition of limestone is re-absorbed from the atmosphere by concrete due to a chemical reaction called carbonation. The free lime, $Ca(OH)_2$, in the pores of the concrete reacts with the atmospheric $CO_2$ and produces $CaCO_3$. This chemical reaction, $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$, is what is commonly described as the carbonation of concrete. Sometimes it is mistakenly referred as the reaction process involved in the hardening of concrete. Hardening of concrete is an entirely different reaction involving hydration of cement which does not have any $CO_2$ implications. The carbonation of concrete structures only occurs near the surface of concrete. For a typical concrete structure, the carbonation depth would be about 20 mm from the surface after 50 years. Further, the major part of the CaO in cement is tied up as part of the hardened concrete in the form of calcium silicate hydrates which are not available for carbonation. Therefore, re-absorption of $CO_2$ by concrete during its lifetime would only be a very small proportion, and is not considered in the calculations in this paper. Further discussions and estimates of $CO_2$ uptake by concrete can be found in Pade and Guimaraes [14].

The figures for the two Supplementary Cementitious Materials (SCMs) considered in this study were also sourced from Heidrich et al. [8]. The emission factor adopted for fly ash was 0.027 t $CO_2$-e/tonne. The emission factor adopted for GGBFS was 0.143 t $CO_2$-e/tonne. Both fly ash and GGBFS are by-products of industries (burning coal and producing steel respectively) which would operate regardless of the production of these useful materials. So the emissions quoted here are based purely on activities conducted subsequent to initial production, including capture, milling, refining and transport (100 km) processes.

**Table 2:** $CO_2$ emissions associated with admixture manufacture

| Admixture type | Primary raw mMaterial | Production energy (kWh/L) | $CO_2$ emissions (t $CO_2$-e/L) |
|---|---|---|---|
| Superplasticiser | Polycarboxylate | 0.0037 | $5.2 \times 10^{-6}$ |
| Set accelerating | Calcium nitrate | 0.0380 | $53 \times 10^{-6}$ |
| Mid range water reducing | Calcium nitrate | 0.0290 | $40 \times 10^{-6}$ |
| Water reducing | Lignin | 0.0016 | $2.2 \times 10^{-6}$ |

Concrete often contains admixtures to enhance early age properties, such as the workability and strength development characteristics. In this study, four different admixture types were considered, for which a large manufacturer supplied the typical figures presented in **Table 2**.

It can be seen that the $CO_2$ emissions associated with the manufacture of concrete admixtures are very small. The total volume of admixtures included in a typical mix design is generally less than two litres per cubic metre. Hence, the contribution to the total emissions per cubic metre of concrete is negligible. As a result of this, the $CO_2$ emissions generated by admixtures can justifiably be omitted from the calculations of total $CO_2$ emissions of concrete.

## 5 Emissions due to Concrete Batching, Transport and Placement

Concrete batching is generally conducted at plants located at various strategic positions around a city or town to minimise transport time. Raw materials are mixed in elevated bins and placed directly into concrete trucks for final transport. This process is primarily powered by electricity, with small amounts of other fuels used on each site by small excavators used to move raw materials, etc. Over a six-month summer/autumn period, the energy consumption and production levels of six different concrete batching plants were audited. The average $CO_2$ emissions due to batching per cubic metre of concrete produced were found to be 0.0033 t $CO_2$-e/m$^3$. **Fig. 4** shows the contributions of each energy source to the total $CO_2$ emissions.

The electric mixing equipment is the most significant contributor to the emissions generated by concrete batching. It has been demonstrated in an internal review by a large concrete manufacturer that substantial improvements can be made to the efficiency of batching equipment by commissioning independent electrical contractors to report on the efficiency of

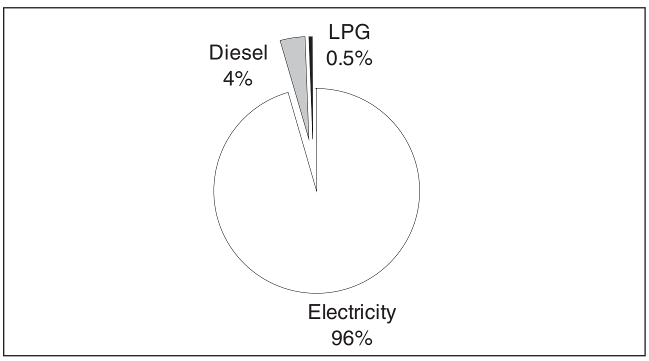


**Fig. 4:** Concrete batching $CO_2$ emissions breakdown

batching equipments and making improvements. Ageing equipment often contains inefficient wiring and switches. Often equipment is left running by old switching equipment during zero load cycles when it could be paused. Thermal losses in poorly planned or low quality wiring can be reduced by replacement. Installation of high efficiency motors can reduce energy demands substantially. However, it should be noted that relative to other components of the concrete production process, the amount of $CO_2$ released through batching activities is fairly low, so it may be more critical to spend money on upgrading other more critical processes.

The transport of batched concrete consumes diesel fuel. Through trucking records taken over a five month period, the average amount of fuel consumed per cubic metre of concrete transported was found to be 3.1 l/m$^3$, which was found to be responsible for 0.009 t $CO_2$-e/m$^3$. Note that this figure includes empty return trips, since the total fuel consumption for the entire fleet of trucks was used. Since the trucking records included trucking to and from a wide range of construction sites and batching plants, it was assumed that the distances travelled were average for metropolitan concrete transport activities.

On-site placement activities such as pumping, vibrating and finishing concrete consume liquid fuels. The amount of diesel consumed to pump one cubic metre of concrete was found to be approximately 1.5 l/m$^3$, found by a survey of local pumping companies. The quantities of fuel consumed by other placement activities were impossible to accurately quantify, due to a lack of records and consistency between sites. Occasionally, concrete is craned into place instead of pumped, and this was also impossible to quantify. Hence, the original figure of 1.5 l/m$^3$ was doubled to account for all other placement activities. The final figure of 3 l/m$^3$ was assumed to be purely diesel fuel, and was found to be responsible for emissions of 0.009 t $CO_2$-e/m$^3$. This is a conservative figure, which is important since in very tall buildings, for example, the amount of fuel consumed by pumping could be higher than the average estimate, and the slack in this estimate allows room for such anomalies.

## 6 Summary of $CO_2$ Emissions

The emissions associated with each activity in the concrete production and placement process were combined into a total figure based on mix design. The factors that were found are summarised in **Table 3**.

## 7 Emissions Generated by Typical Commercially Produced Concretes

To investigate two of the methods by which the amount of $CO_2$ generated by concrete can be reduced, four mixes were selected with binders including Supplementary Cementitious Materials (SCMs). The first two mixes (25 MPa and 32 MPa) have 25% of the GP cement replaced by fly ash. The second two mixes (25 MPa and 32 MPa) have 40% of the GP cement replaced by GGBFS. These percentages are chosen because they are commonly used in construction projects. It is noted that large cement replacements in lower grade concretes such as these will not result in efficient construction because properties such as set time and early strength development can be affected. 25 MPa and 32 MPa concretes are commonly used standard strengths. **Table 4** and **Fig. 5** below show the results of this analysis, with two Type GP cement concretes as a benchmark.

Type GP cement is the dominant source of emissions in all of the concretes, blended or otherwise. The fly ash blended concretes show reduced $CO_2$ emissions (13–15%), but it is the GGBFS blended concretes that show more substantial reductions (22%). This is because more GGBFS is typically included in a blended mix without significantly changing the engineering properties of the concrete, due to its natural cementitious properties. So while GGBFS has a higher material emission factor than fly ash, it can replace more cement, which leads to lower total emissions.

**Table 3:** Final $CO_2$ emission factors

| Activity | Emission factor | Unit |
|---|---|---|
| Coarse aggregates – Granite/Hornfels | 0.0459 | t $CO_2$-e/tonne |
| Coarse aggregates – Basalt | 0.0357 | t $CO_2$-e/tonne |
| Fine aggregates | 0.0139 | t $CO_2$-e/tonne |
| Cement | 0.8200 | t $CO_2$-e/tonne |
| Fly ash (F-type) | 0.0270 | t $CO_2$-e/tonne |
| GGBFS | 0.1430 | t $CO_2$-e/tonne |
| Concrete batching | 0.0033 | t $CO_2$-e/m$^3$ |
| Concrete transport | 0.0094 | t $CO_2$-e/m$^3$ |
| On aite placement activities | 0.0090 | t $CO_2$-e/m$^3$ |

**Table 4:** $CO_2$ emissions generated by typical commercially produced concretes

| | 100% GP Cement | | 25% Fly Ash | | 40% GGBFS | |
|---|---|---|---|---|---|---|
| Strength (MPa) | 25 | 32 | 25 | 32 | 25 | 32 |
| Emissions (t $CO_2$-e/m$^3$) | 0.290 | 0.322 | 0.253 | 0.273 | 0.225 | 0.251 |
| % $CO_2$ Reduction | 0% | 0% | 13% | 15% | 22% | 22% |

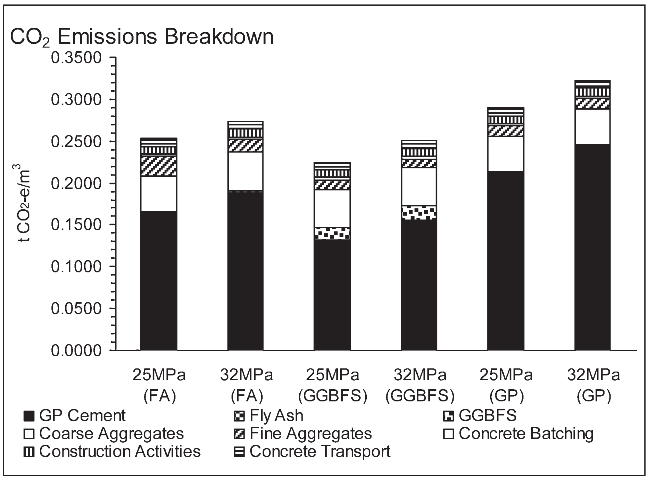


**Fig. 5:** $CO_2$ emissions generated by typical commercially produced concretes

## 8 Case Study – The Role of Concrete in Sustainable Buildings

The result of a design competition held in 2001 by the Victorian Office of Housing, the K2 public housing project in Melbourne, Australia is an excellent example of innovative sustainable building design. The competition required the core structure to have a 200 year life span, generate renewable energy on-site, consume no non-renewable energy and halve mains water consumption [12]. In the final design, currently under construction, these requirements have been subjected to some interpretation, but generally they have all been achieved in some capacity. The winning design, by architects DesignInc Melbourne Pty Ltd, supported by engineering firm Arup, features four medium rise buildings, with a total of 96 apartments suitable for public housing.

The main Environmentally Sustainable Design (ESD) features of the design are: maximised incident solar energy through building orientation; passive ventilation through building orientation and apartment design; photovoltaic cells for on-site renewable energy generation; strategic placement of thermally massive materials for energy storage; strategic placement of insulation to prevent unwanted energy migration; use of low embodied energy materials (structural and otherwise); solar powered hydronic heating for extreme winter weather; grey and storm water recycling; water efficient appliances and fittings.

Based on predictive models compiled by the design team, it can be estimated that the probable annual operational energy consumption at K2 (lighting, elevators, hot water and appliances) will be approximately 1000 MWh, depending on ongoing tenant education and choice of appliances [13]. This energy is sourced from both electricity and natural gas. Note that depending on the uptake of tenant education, annual operational energy could be substantially lower than this, under the predicted best case scenario. The most probable energy consumption scenario was used for this case study.

When predicting the total operational energy consumption over the lifespan of the structure, it is appropriate to consider only 100 years of operation. Due to the demographic changes expected over 100 years, the purpose of the structure may change after that period of time. Hence, it is expected that a major refit will be required after 100 years. According to the design team's probable development scenario, 1000 MWh/year equates to approximately 850 t $CO_2$-e/year including contributions from both gas and electricity. Hence, over 100 years, building operations will generate a total of approximately 85000 t $CO_2$-e.

This figure is based on the current electricity and gas emission factors. However, the methods of electricity generation in Melbourne may change substantially over the next 100 years, from burning brown coal to more sustainable techniques.

It is now interesting to investigate the initial material based $CO_2$ emissions associated with concrete. There are a range of other sources of initial $CO_2$ emissions at K2, including glass, steel, aluminium, photovoltaics, and fitout materials, however, this investigation will focus on concrete alone.

Based on the K2 bill of quantities and the component emission factors outlined earlier, the volumes of concrete and associated target $CO_2$ equivalent emissions shown in **Table 5** were found. On average across the whole structure, the design target is to replace 30% of total Portland cement with fly ash. Note that this target has not yet been achieved, since construction is not complete.

**Table 5:** Concrete volumes and target embodied energy $CO_2$ emissions

| Strength (MPa) | Structural element | Quantity ($m^3$) | Emission factor (t $CO_2$-e/$m^3$) | Emissions (t $CO_2$-e) |
|---|---|---|---|---|
| 15 | Blinding | 589 | 0.20 | 119 |
| 32 | Footings | 489 | 0.24 | 119 |
| 32 | Slabs | 1948 | 0.27 | 533 |
| 40 | Insitu Columns & Walls | 235 | 0.27 | 63 |
| 40 | Precast Walls | 1067 | 0.33 | 351 |
| | | | | 1185 |

To quantify the target $CO_2$ savings that will be made by substituting fly ash for some of the cement content of the concrete, a similar investigation was performed using mix designs containing only pure GP cement. The total $CO_2$ equivalent emissions generated by the pure GP cement based concretes were found to be 1391 t $CO_2$-e. Hence the target savings that will be made by replacing a portion of the GP cement with fly ash are approximately 206 t $CO_2$-e.

According to the design team's estimated energy consumption as described earlier, the yearly $CO_2$ emissions associated with building operations will be approximately 850 t $CO_2$-e/year. Over the 100 year building lifespan, the $CO_2$ emissions generated by the structural concrete will be less than 1.4% of the emissions associated with operation, assuming all design targets are met.

Furthermore, as a result of the energy efficient design of K2, the most probable estimated energy consumption is already expected to be reduced by 57% [13], or approximately 1125 t $CO_2$-e/year. So by designing the building with passive energy measures and educating the tenants to minimise energy consumption, the target tonnage of $CO_2$-e that will be saved per year will be over five times greater than that predicted to be saved initially by the use of fly ash in the structural concrete. Hence, over 100 years, the tonnage of $CO_2$-e that will be saved due to the efficient building design will be approximately 500 times greater than that estimated to be saved by the use of fly ash in the structural concrete, again assuming all design targets are met.

This case study shows that passive design measures, which enhance the operational energy performance of a building, have the potential to make a greater impact on the overall greenhouse gas emissions of a building than using fly ash substitution in concrete mix designs. However, the short to medium term benefits of using low embodied energy concretes are still significant and valuable. It is worth noting that using fly ash in structural concrete results in accurately quantifiable capital $CO_2$ savings. Passive energy measures have the capacity to be more effective in the long term, but depend on a large number of variables, such as tenant behaviour, which can be difficult to control.

This case study also shows that for comparison of $CO_2$ emissions of alternative construction materials such as steel with concrete, the emissions associated with concrete should be considered rather than just the cement component alone, since emissions due to cement are only part of the concrete emissions, albeit a significant part.

## 9 Conclusions

While there have been many studies conducted to estimate the $CO_2$ emissions due to Portland cement manufacture, very few reliable estimates are available for the emissions due to concrete manufacture. The figures for the emissions for two types of coarse aggregates, fine aggregates, cement, fly ash, slag, concrete batching, transport have been developed based on large number of records obtained from aggregates quarries, concrete batching plants and other sources. Although the data presented above was collected from locations around Melbourne, Australia, it can be used as a guide to estimate the emissions due to concrete production and placement in other parts of the world with similar production methods.

The following conclusions can be drawn from the data collected in this study:

1. The equivalent $CO_2$ emissions generated by a particular concrete with known mix proportions can be estimated using the emissions contributions from the constituents of concrete.
2. Portland cement was found to be the primary source of $CO_2$ emissions generated by typical commercially produced concrete mixes, being responsible for 74% to 81% of total $CO_2$ emissions.
3. The next major source of $CO_2$ emissions in concrete was found to be coarse aggregates, being responsible for 13% to 20% of total $CO_2$ emissions.
4. The majority contribution of $CO_2$ emissions in coarse aggregates production was found to from electricity, typically about 80%. Blasting, excavation, hauling and transport comprise less than 25%. While the explosives have very high emissions, they contribute very small amounts (<0.25%) to coarse aggregate production, since only small quantities are used.
5. Production of a tonne of fine aggregates was found to generate 30% to 40% of the emissions generated by the production of a tonne of coarse aggregates. Fine aggregates generate less equivalent $CO_2$ since they are not crushed.
6. Diesel and electricity were found to contribute almost equally to the emissions due to fine aggregates.
7. Emission contributions due to admixtures were found to be negligible.
8. Concrete batching, transport and placement activities were all found to contribute very small amounts of $CO_2$ to total concrete emissions.
9. The $CO_2$ emissions generated by typical normal strength concrete mixes using Portland cement as the only binder were found to range between 0.29 and 0.32 t $CO_2$-e/m$^3$.
10. GGBFS was found to be capable of reducing concrete $CO_2$ emissions by 22% in typical concrete mixes.
11. Fly ash was found to be capable of reducing concrete $CO_2$ emissions by 13% to 15% in typical concrete mixes.
12. The target $CO_2$ emissions due to the structural concrete at the sustainable apartment complex considered as a case study will form less than 1.4% of the estimated probable total lifetime $CO_2$ emissions generated by the building. Note that the award winning design of this particular building is estimated to reduce operational energy consumption by 57% under the most probable operational scenario compared to a typical conventional apartment building of comparable size designed without any ESD features.
13. The case study showed that passive design measures, which enhance the operational energy performance of a building, have the potential to make a greater impact on the overall greenhouse gas emissions of a building than using fly ash substitution in concrete mix designs.

## 10 Recommendations and Perspectives

The various rating schemes used to compare alternative construction materials should use models such as the one presented in this paper based on hard data so that reliable comparisons can be made. A case study is presented in the paper demonstrating how the results may be utilized.

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## References

[1] Jönsson Å, Björklund T, Tillman A-M (1998): LCA of Concrete and Steel Building Frames. Int J LCA 3 (4) 216–224
[2] Schuurmans A, Rouwette R, Vonk N, Broers J, Rijnsburger H, Pietersen H (2005): LCA of Finer Sand in Concrete. Int J LCA 10 (2) 131–135
[3] Humphreys K, Mahasenan M (2002): Toward a Sustainable Cement Industry. Substudy 8, Climate Change. World Business Council for Sustainable Development
[4] Commonwealth of Australia (2004): Australian Greenhouse Office Factors and Methods Workbook. Australian Greenhouse Office
[5] Cuevas-Cubria C, Riwoe D (2006): Australian Energy: National and State Projections to 2029–30. Australian Bureau of Agricultural and Resource Economics
[6] CIF (2003): Cement Industry Environment Report, Cement Industry Federation
[7] Collins F, Sanjayan J G (2002): The Challenge of the Cement Industry Federation Towards the Reduction of Greenhouse Emissions, Towards a Better Built Environment – Innovation, Sustainability, Information Technology. Proceedings of the International Association of Bridge and Structural Engineers Symposium, Melbourne
[8] Heidrich C, Hinczak I, 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, Sydney
[9] John VM (2003): On the sustainability of concrete. UNEP Industry and Environment, pp 62–63
[10] Gartner E (2004): Industrially interesting approaches to 'low $CO_2$' cements. Cement and Concrete Research 34, 1489–1498
[11] Josa A, Aguado A, Heino A, Byars E, Cardim A (2003): Comparative analysis of available life cycle inventories of cement in the EU. Cement and Concrete Research 34, 1313–1320
[12] Office of Housing internet site (2005): http://hnb.dhs.vic.gov.au/ooh/oohninte.nsf/frameset/Ooh?Opendocument, accessed 9 August 2005, last updated 20 July 2005
[13] Personal communication with John MacDonald, DesignInc Melbourne Pty Ltd, 15 July 2005
[14] Pade C, Guimaraes M (2006): The $CO_2$ Uptake of Concrete during a 100 year Perspective, Proceedings of Advances in Cement and Concrete X – Sustainability. Davos, Switzerland, July 2006, Engineering Conferences International, pp 114–119

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