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Measuring the Embodied Carbon Content of Concrete Paving

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Abstract: This paper summarises the outcomes of a PhD research project by Richardson (2009) to measure the embodied carbon content of concrete paving and to reveal the barriers to its accurate measurement. This is a current area of research due to the concerns arising from the anthropogenic emission of carbon dioxide which has been identified as a key cause of climate change. The work was carried out in co-operation with a major manufacturer of concrete paving revealing the practicalities of energy auditing within an existing factory using its unmodified infrastructure, methods of energy metering and recording. The work involved identifying all of the energy inputs involved in the manufacturing process during a financial year. The auditing boundaries were restricted to the main manufacturing facility and its immediate suppliers of raw materials commonly known as cradle to gate. The energy applicable to the paving material had to be apportioned from site wide energy usage. The energy used to supply the raw materials and operate the manufacturing facility was then converted to an amount of carbon dioxide released using standard conversion factors. The barriers to accurate auditing were identified and an embodied carbon coefficient for the raw materials and finished product determined. The embodied carbon contents that were determined differed from those found in the national database. A number of factors are identified that could have contributed to this and suggestions for further research made.

Introduction

It is now widely accepted by the scientific community that the release of carbon dioxide (CO_2) into the atmosphere from fossil fuel based energy use is a major contributor to climate change. In the United Kingdom (UK) the construction and operation of buildings has been identified as supplying almost half of the CO_2 discharged into the atmosphere each year (Drummond, P., & Ekins, P. 2016). It can be seen then that reducing the energy used to construct and operate buildings is key to reducing the overall UK CO_2 output. To date, the main focus has been given to reducing the energy used in the operation of buildings. In the UK this is primarily consumed by space and water heating systems but also includes other building services installed in the premises including, lighting, fans and pumps and in some buildings air conditioning and mechanical movement systems. Much legislation has recently been implemented to reduce the operational energy use of new buildings. This includes changes to Part L of the Building Regulations (Department for Communities and Local Government 2016) which includes elements of the EU Energy Performance of Buildings Directive (European Union 2010). The aim of this legislation is to reduce the CO_2 output arising from fossil fuel energy consumption in buildings with an ultimate aim of producing zero CO_2 buildings. For example it was the UK governments target to reduce the carbon output of new housing to zero by 2016 (Department for Communities and Local Government 2009). This ambitious target has now been relaxed but if it were to be achieved then the focus of attention would shift onto the energy used and hence CO_2 emitted during the extraction and manufacture of materials and the construction of buildings from those materials. Even with low but not zero CO_2 buildings it has been estimated by Troy, P., Holloway, D., Pullen, S., & Bunker, R. (2003). that, in some buildings, embodied carbon will be greater than the amount of operational carbon for many years and in some cases, with short building lives, may be the dominant energy use over the whole life of the building.

A number of studies have considered the issue of embodied energy previously including Miller (1997), Alcorn (1998), Miller (2001) and Scheuer, Keoleian, & Reppe (2003). This study adds to that body of knowledge by focussing on a specific product and continues moving the focus of attention from units of energy used to amount of CO_2 released. This is important because the amount of CO_2 released is a better indicator of environmental impact than the number of energy units consumed. This is because the consumption of different forms of energy results in the release of different amounts of CO_2. For example 1kWh of energy from a renewable source, such as wind power as a result of its embodied energy releases very little CO_2 whereas the same unit of energy from a highly processed source such as mains electricity results in the release of a relatively large amount of CO_2 into the atmosphere.

The research was carried out in collaboration with a local manufacturer and their raw material suppliers. At the time of the research the works had a long history, having been first established to produce natural stone products. It now produces a range of concrete based landscaping and building products for the international market. The operators of the site are very environmentally aware and are constantly seeking ways of reducing the environmental impact of their operations. Part of this ongoing commitment was to collaborate with this research project. The site is a useful choice for this project in that it is a well-established site, reflective of much of the UK manufacturing infrastructure. It has the added complexity, again shared by other manufacturers, of using the same plant to produce more than one product.

The product that is the subject of this research is the natural (uncoloured) pre-cast concrete paving slabs. This is referred to throughout the text as ’concrete paving’. The embodied carbon content arrived at through this research will be compared with figures contained in the authoritative Inventory of Carbon and Energy Database (Hammond & Jones 2008)

The Auditing Boundaries

One of the decisions that has to be made when embarking on an embodied carbon audit is the need to define the boundaries between which the audit will be carried out. The simplest set of boundaries is those either side of the main manufacturing facility. This is because the energy used is more easily defined and simply requires the auditing of energy use using the main utility meters and sub meters on site. However, the concern here is that the CO_2 output from suppliers of raw materials to the site remains unknown and with some materials this could be significant. For the purpose of this research it was therefore decided to include both the raw materials supply chain from the point of abstraction of the source materials from the environment (cradle) and the main manufacturing facility up to the point where the finished product exits the factory (gate) in the audit. The raw material suppliers can be identified from the components of the product mix which are ordinary Portland cement, 6mm to dust sandstone, 5mm to dust limestone and mains water.

Energy uses beyond these boundaries such as the supply of products and services to the raw material companies and main manufacturing facility were not included in the audit. The reasons for this are twofold; the difficulty in identifying and auditing tertiary sources and secondly due to insignificant share of energy used in these sources when apportioned to each slab.

Direct and Indirect Energy Use

The energy needed to manufacture products includes both direct and indirect energy consumption. Direct energy use is defined as that required by the buildings, vehicles and the fixed and mobile plant that play an active part in the extraction, handling, processing and transportation events that form the material supply chain. Indirect energy uses are those events that occur in the background to support the direct activity. Both types of energy use are essential to the overall process as without them the supply chain could not function. Both direct and indirect energy use were audited.

Examples of Direct energy use are;

- Energy consumed by fixed and mobile plant to extract raw materials and transport them.
- Energy used to process materials for example crushing or heating.
- Energy consumed by fixed and mobile plant that is used to manufacture the finished product in the factory.

Examples of Indirect energy use are;

- Energy used to heat and light the stakeholder facilities.
- The maintenance of a stakeholder's buildings, plant and vehicles.
- Staff commuting, including those employed by outside catering, cleaning and maintenance companies.
- The heating/lighting of the administration buildings and running of office equipment.

Auditing Method

A number of forms of energy are used across all of the stakeholders. Quantities of energy used were measured or had to be estimated. The range of techniques used to estimate energy consumption data included;

<u>Vehicle fuel consumption</u>

Fuel consumption was estimated by dividing the distance travelled in kilometres (km) by the vehicle fuel consumption obtained from the logistics manager, in kilometres per litre (km/l). When carrying heavy products such as stone the fuel consumption of vehicles is markedly different in the loaded and unloaded state. In this case round trip distance and the average of the loaded and unloaded fuel consumption was used. Round trip distances were obtained using on-line route planning software by entering departure and destination postcodes.

<u>Electricity and gas</u>

This energy input data was obtained from utility meter readings. However, in many cases the readings represented the energy used site-wide rather than exclusively for the production of concrete paving. This issue was applicable to both raw material suppliers and main manufacturing facility. When this situation occurred, that part of the overall energy use related solely to the provision of a raw material or to concrete paving manufacture had to be estimated. This was carried out on a ‘by weight’ basis. Using the sandstone component as an example, the Quarry in question produced 510,000 tonnes of sandstone during the audit period 120,000 tonnes of which was the 150mm clean sandstone supplied to the Manufacturing Works, or 23.53% of total production output (personal communication made 19-04-07). It follows therefore that a reasonable estimate is to assume 23.5% of all Quarry energy used was associated with the concrete paving manufacture.

Raw Materials

This section gives a description of the energy using processes involved in supplying the raw materials required for the concrete paving to the manufacturing works. For most of the stakeholders a site visit was carried out to identify where energy was being consumed by the production process.

<u>Cement</u>

The Portland cement used to manufacture the natural concrete paving is sourced from a large UK Cement supplier. The main energy input events are; manufacture of the cement, transport to a distribution depot by rail and finally transport to the manufacturing works by road. Cement manufacture is a very energy intensive process requiring a number of energy input events (Lafarge Cement UK (LCUK) 2005).

<u>5mm to Dust Limestone</u>

The 5mm to dust limestone component of the mix used to manufacture the concrete paving is sourced from a quarry in the Yorkshire Dales National Park.

The primary processing of limestone extraction at the quarry uses much heavy plant such as tracked bucket loaders and crushers. However it is modern, well maintained and highly energy efficient equipment.

The secondary operation involves all further handling, processing and loading phases. This utilises conveyor belt systems, vibrators and tertiary crushers. The 5mm to Dust Limestone destined for the Manufacturing Works is collected from the silo and delivered by road by heavy goods vehicle (HGV).

<u>150mm Clean Sandstone</u>

The 150 mm clean sandstone component of the mix used to manufacture the concrete paving is sourced from the Manufacturer's own quarry in Lancashire. 120,000 tonnes of this are supplied each year.

The production of 150mm clean sandstone has been divided in to two specific operations, the primary operation involves pulling the rock from the quarry face using CAT 360^0 caterpillar tracked excavators. Where the rock is difficult, or too dangerous to dislodge using these machines, it is removed using explosives. The caterpillar tracked excavators then place the dislodged rock into a large stockpile.

The secondary operation involves two stages. The first stage, involves the use of two Daewoo 420 Breakers that use their hydraulic rammer to split the stone into blocks with edges around 600mm long. A tracked Loading Shovel then loads these into a primary Crusher. Subsequent to crushing taking place, the stone is conveyed to a screen to grade in to three sizes. The three sizes are 'Fine grains to 40mm', '75mm Clean' and '150mm Clean'. It is the latter size that is used at the Manufacturing Works and so is loaded onto waiting Class 1 HGV's using a tracked loading shovel.

This quarry is in an extremely remote elevated location having no access to any mains services. For this reason gas oil is the energy source for all the plant and generators that are used at this quarry. The quantity of gas oil that was consumed by the mobile plant is recorded on site via an automatic fuel monitoring system.

<u>Water</u>

A considerable amount of water is used to manufacture concrete products. The volume of mains water consumed at the Manufacturing Works is metered. The volume associated with the concrete paving was determined on the by-weight of total production basis described earlier. Ascertaining the embodied carbon dioxide content of mains supplied water would be difficult to determine from monitoring and so an accepted embodied energy of 1.2 kWh/m^3 was used (Coley, D.A. 1995). This was converted to a carbon dioxide output using the emission factor for electricity (0.43kg CO_2/kWh), based on the knowledge that electricity is the energy source used for treating, pumping and circulation of water.

Product Manufacturing Works

All of the raw materials are assembled into the final natural concrete paving product at the Manufacturing Works. This section looks at the direct and indirect energy used.

<u>Direct energy usage</u>

The manufacture of the paving product is comprised of the following three distinct direct energy demanding stages:

- Receipt, processing and handling of raw materials;
- Mixing, pressing, handling and curing of the finished product; and finally
- Packaging and handling of the finished product.

One element of the first stage that required a considerable amount of energy, involved crushing the 150mm clean sandstone down to the 6mm to dust product that is required by the mix. The energy required by the Norberg crusher is substantial and so has been sub metered. Meter readings are recorded at half hourly intervals. As an illustration, Figure 1 shows the electrical energy consumption of the crusher measured at half hourly intervals over a typical working day.

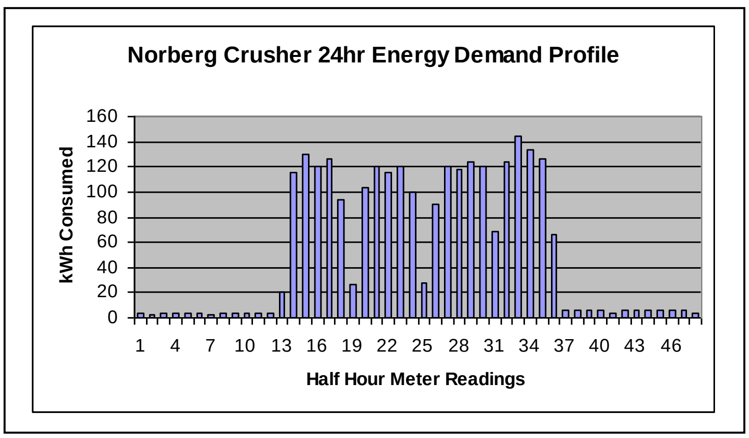

Figure 1: Norberg Crusher 24 hr Energy Demand Profile for one day.

From this figure it can be seen that on this day the maximum half hourly consumption was 144 kWh, the minimum consumption was 2 kWh and the total consumption across the whole 24 hour period was 2,566 kWh.

Production data and details concerning the fixed and mobile plant used relating to the second and third direct stages was provided by the Manufacturer and site visits. This information was used to construct table 1, so that the processes and plant involved could be more easily visualised.

Event	Item of Plant	Powered Components	Energy Source	Task being undertaken
Mixing source materials	Haarup mixer	Electric motor	Electricity 22 kW	Mix source materials with water to produce concrete
Transfer of concrete	Screw feed pipe	Electric motors	Electricity 1.5 kW & 4 kW	Screw feed pipe transfers concrete from the mixer to the paving press
Produce pavers	Paving press	Turn table Hydraulic press pump	Electricity 22 kW 22 kW	A three mould turntable enables one mould to be filled, whilst one is being pressed and at the same time the paving product of the third mould is being ejected onto the tippler, which places the green paving product onto a pallet.
Transfer pallet of pavers	Fork lift truck		LPG	Once the required number of pavers has been placed on a pallet, they are then transported to the curing racks.
Curing the product	Curing racks		Natural gas	Curing of the paving product takes twelve hours, the process being enhanced by circulating warm air through the racks.
Transfer pavers to banding machine	Fork lift truck		LPG	
Bind pack of pavers	banding machine		Electricity 0.75 kW	In the case of the 450x450x50mm pavers, 40 units are bound together to form a pack.
Transfer pavers to the shrink wrap machine	Fork lift truck		Gas oil	
Shrink wrap pavers	Shrink wrap machine		Natural Gas	Pack of pavers is first placed on a timber pallet, before being wrapped in polythene by the shrink wrap machine. Product and Batch Code labels are inserted at this point.
Transfer pavers to yard	Fork lift truck		Gas oil	Pavers held in yard for at least one week.
Wash down components	Water pump	Haarup mixer Screw feed pipes Paving press	Electricity 36 kW	Slurry produced from wash down is first filtered then pressed to produce a waste cake that is left to dry naturally. 0.0021kg of waste cake is produced per tonne of product manufactured. Dried cake is eventually disposed as landfill, when a viable amount has been collected.
Load pavers onto delivery vehicle	Grab truck		Gas oil	Grab truck loads the required number of banded and wrapped paving product packs onto one of the company's flat backed delivery vehicles. Hydraulically operated hiab powered by the vehicles engine is used to facilitate the offloading process.

Table 1: Paving Product Manufacture to Factory Gate Energy Input Events.

<u>Indirect energy usage</u>

Indirect activity associated with the manufacture of the natural paving product took a number of forms including machinery maintenance and administration. Both elements were considered. The former by recording the number of site visits by maintenance personnel and determining their round trip distances and vehicle usage. The latter was the largest input and included such activities as processing payroll, personnel issues and orders and payments. These functions are carried out in a separate head office. However, the head office carries out administration related to all of the products made by companies within the Manufacturers group not just the natural concrete paving. It was therefore necessary to apportion administration energy use to that associated solely with the paving product being investigated. This was again carried out on a by-weight basis but this time it was based on the weight of the output of concrete paving from the Manufacturing Works to total weight of output from those other elements manufactured by the group administered from head office. It was found natural concrete paving output represented 1.52% of the group's total output. This percentage was used to calculate the proportion of the yearly gas and electricity consumption of the head office to associate with the natural concrete paving. The energy associated with the daily commute by staff employed at Head Office was determined by issuing a questionnaire to staff. This asked for details of commuting for example car share, public transport or own car. Where cars were used actual round trip distances from home to work were specified and also make, model and engine capacity of vehicle. Fuel consumption figures were then obtained from individual motor manufacturers.

The preceding sections described how energy was identified and measured across the various contributors. The process of converting this to a CO_2 output was carried out using a series of excel workbooks to record fuel usage, determine the amount of this to be associated with the concrete paving, convert fuel to energy units, convert energy to a carbon dioxide output (based on the type of fuel) and finally aggregate the amounts of CO_2 together. Stages are described further below.

<u>Energy to carbon conversion</u>

A variety of energy sources were used by the stakeholders. Electricity use is directly recorded as an amount of energy in kilowatt hours by the utility meters. However, other fuels need to be converted into an amount of energy. This was achieved by multiplying the quantity of fuel used by its calorific value. The calorific values used in this project are provided by the Carbon Trust (2006) and shown in table 2.

Fuel	Calorific Value
Petrol	10.0 kWh/litre
LPG	7.4 kWh/litre
Gas/Diesel oil	10.8 kWh/litre
Fuel Oil	11.9 kWh/litre
Natural gas	11.0 kWh / m^3

Table 2: Calorific Values.

The amount of CO_2 released per kilowatt hour of energy consumed depends on the fuel type. Converting quantities of energy used to a CO_2 output was achieved by multiplying the amount of each form of energy used in kilowatt hours by a standard conversion factor in kilograms of CO_2 per kilowatt hour. The conversion factors used are provided by The Carbon Trust (2006) and are shown in table 3

Energy and Fuel Consumed	**Emission Factor ($KgCO_2$/kWh)**
Electricity from grid	0.43
Fuels	
Natural gas	0.19
Gas/diesel oil	0.25
Petrol	0.24
Heavy fuel oil	0.26
LPG	0.21

Table 3: Carbon Dioxide Emission Factors for Energy Related Emissions.

Research results

The main aim of the project was to determine the amount of carbon dioxide released as a result of the energy consumed to supply raw materials and manufacture a natural concrete paving product.

The embodied carbon content of natural concrete paving measured using the auditing boundaries of cradle to gate was found to be 0.166kg $kgCO_2$/kg. For the 450 x 450 x 50mm product this equates to a CO_2 output per unit area of 17.84kg CO_2/m^2

The embodied carbon content of the cement component measured up to the receipt of delivery at the Manufacturing Works was found to be 0.834kg CO_2 /kg

The embodied carbon content of the 150mm clean sandstone component measured up to receipt of delivery at the Manufacturing Works was found to be 0.0096kg CO_2/kg

The embodied carbon content of 5mm to dust limestone measured up to receipt of delivery at the Manufacturing Works was found to be 0.0067kg CO_2/kg

Discussion

Values are necessary with which to compare the values of embodied carbon determined by this research project in order to highlight gross errors and make a comparison. The most widely used UK database of embodied carbon dioxide for building materials is the Inventory of Carbon and Energy (ICE) compiled by Hammond and Jones at the University of Bath (2008). The research results and ICE database values are shown in table 4. Before comparing these values it is worth comparing the values by the research for the processed and delivered limestone and sandstone. It is reassuring that whilst the embodied carbon value for sandstone is 43% larger than that for limestone that they are of a similar order of magnitude which is to be expected since they have similar energy input events associated with them. Both extracted from a quarry, underwent crushing and finally were delivered to the Works by road transport.

Material	Research Results ($kgCO_2/kg$)	ICE Database Values ($kgCO_2/kg$)
Concrete Paving	0.166	0.127[1]
Cement	0.834	0.93[2]
Sandstone	0.0096	0.058[3]
Limestone	0.0067	0.087[4]

Table 4. Comparison of research results with ICE database values

Considering the comparative table the research value for concrete paving is larger than that found for precast concrete products in the database whereas the values for Cement, sandstone and limestone are all smaller. The research values for sandstone and limestone values stand out as being a much smaller than those in the database.

A number of explanations are possible for these differences.

- The ICE database calculates embodied carbon using a 'typical fuel mix in the relevant UK industry'. It could be that this fuel mix did not reflect the fuel mix found by this research.
- This research is for a specific set of operations whereas some industry generalisations appear in the database
- There may have been some unknown inaccuracies in the research project.
- There may have been variations in handling for example differences in transport or crushing

The research revealed a number of barriers to the accurate auditing of energy usage that could provide more consistent results. These are;

- Vehicle fuel consumption was not metered so it had to be estimated using average fuel consumption figures provided by logistics managers or from the vehicle manufacturer's published fuel consumption figures and distance travelled. Any variation in route travelled from the on-line route planner or fuel consumption (due to driving style or vehicle maintenance issues) would have led to an inaccurate estimate being made.
- The main production facility produced a range of concrete products. Apportioning overall energy use on a 'by-weight' of individual product output compared to total weight of output could lead to inaccuracies. It may, for example, be that different products use machinery differently and so the by-weight allocation of energy may not be appropriate.

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[1] Based on the value for general concrete (0.1 $kgCO_2/kg$) plus a modification factor for precast (prefabricated) concrete (0.027 $kgCO_2/kg$)

[2] Average CEM 1 Portland Cement

[3] Stone sandstone

[4] Stone limestone

- Some energy inputs were considered to make an insignificant contribution to the embodied carbon and so were not included an example is commuting travel fuel usage of staff at raw material extracting sites.

The key suggestion for improving the accuracy of embodied carbon auditing is the introduction of extensive real time energy data acquisition. The technology for this already exists and would involve

- Installation of relevant energy monitoring equipment and software
- Vehicle telemetry to record fuel usage
- Sub metering of fixed and mobile plant associated with production lines

This data would need to be fed into a product batch database in real time and be aggregated to give a total. This would mean that as well as associating such items as quality assurance to a particular batch it would also be possible to state the energy consumed and hence CO_2 output produced during its manufacture.

Conclusion

The investigation carried out the main objective of measuring the embodied carbon content of concrete paving as manufactured and those of its main components. The second was to identify the barriers to the accurate auditing of energy use and hence CO_2 outputs. The embodied carbon results as found do show differences to values found elsewhere. The differences are likely to occur as embodied carbon measurement is still at an early stage and differences may arise in the range of energy input events and the auditing of these.

Standard auditing boundaries have been accepted, energy to CO_2 conversion factors have been agreed, however the outstanding issue preventing the accurate recording of CO_2 emissions for a particular batch of product remains that of real-time monitoring of energy usage along the production line. Sometimes this production line is discontinuous and so some method of accurately passing on energy use to proceeding stages would be needed. It is suggested therefore that further research should take place into the application of remote monitoring of energy consumption using multiple sub metering feeding data into a centralised data storage system.

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