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Cradle-to-gate environmental impacts of the concrete industry in South Africa

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The objective of the paper is to provide an understanding of the South African concrete industry's environmental burden in terms of natural resource consumption and carbon dioxide equivalent emissions (CO_2-e). The review covers current practices in the concrete construction field in South Africa (SA) and their implications for the environment. Elaboration in terms of detail and quantification is given for the environmental burden generated during the manufacture of raw materials for concrete and their transportation to site. Four-year average (2005–2008) data is provided for resources consumed and wastes emitted during the quarrying and manufacture of raw materials for concrete. Carbon dioxide-equivalent emissions data per unit of material produced was obtained from the InEnergy Report produced for the Cement and Concrete Institute (C&CI) of South Africa. The study determined that, on average, 39.7 Mt of raw materials are consumed per year and 4.92×10^9 kg CO_2-e emissions are emitted per year to produce cement and aggregates for concrete production in South Africa.

INTRODUCTION

Background

In the mid-20th century and beginning of the 21st century, the increased uptake of concrete as a structural material has led to sustainability issues. The worldwide consumption of concrete has been estimated to be increasing gradually from 6.4 billion m^3 in 1997 (Aïtcin 2000) to 8 billion m^3 in 2009 (CEMBUREAU 2011). This amount will continue to increase, particularly in the developing countries, due to an exponential increase in population growth, urbanisation and economic growth.

However, while concrete production continues to grow and contribute towards socio-economic development, evidence suggests that this growth is associated with an escalating negative and irreversible impact on the environment.

The main purpose of this paper is to provide an understanding of the South African concrete industry's environmental impact in terms of natural resource consumption and CO_2-e emissions. The review covers current practices in the concrete construction field in South Africa (SA) and their implications for the environment. Elaboration in terms of detail and quantification is given for the environmental impact generated during the manufacture of raw materials for concrete and their transportation to site. Four-year average (2005–2008) data is provided for resources consumed and wastes emitted during the quarrying and manufacture of raw materials for concrete.

South African concrete industry

The concrete industry in South Africa comprises cement manufacturers, aggregate producers, admixture suppliers, cement extender (fly ash and slag) suppliers, ready-mix and precast concrete producers, concrete product manufacturers (including producers of cement building blocks, fibre cement roof sheets, concrete pipes and concrete roofing tiles), designers of structural concrete (civil and structural engineers), building and civil engineering contractors, and small-scale cement and concrete product consumers (e.g. home builders).

The activities of the South African concrete industry have been more pronounced in the recent past due to government and private industry investment in new (and replacement) construction of 2010 FIFA World cup stadia and other infrastructure projects, e.g. the Gautrain Rapid Rail Link, airports, and so on. Further consumption of large quantities of energy and resources for concrete production is expected in the foreseeable future to meet the demands of the rapidly expanding population.

This paper investigates the resource flows and carbon dioxide equivalent (CO_2-e) emissions generated from the manufacturing activities of concrete construction materials in SA for the period 2005 to 2008. The resource flows are the raw material use (tonnes), and the CO_2-e emissions are anthropogenic CO_2 emissions and other greenhouse gases (GHG) such as NO_2 and SO_2.

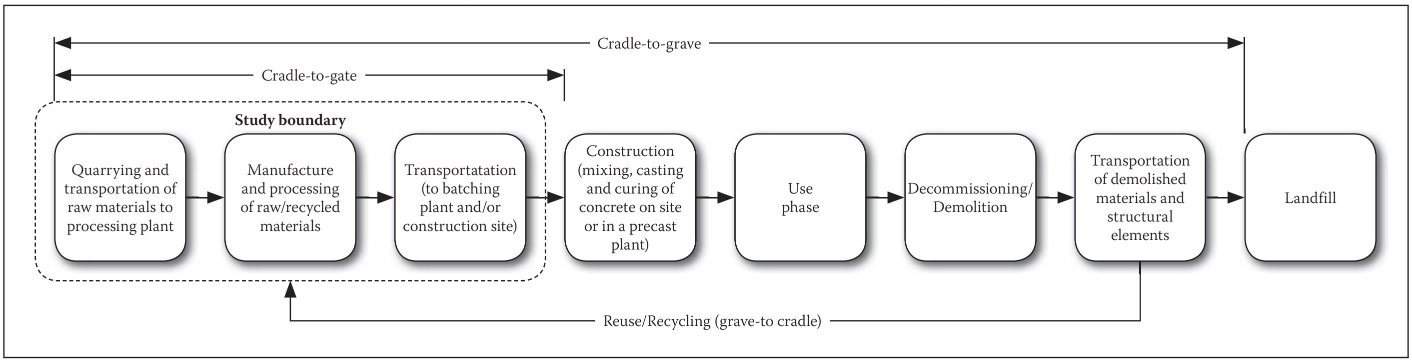

Figure 1 Life-cycle phases of a concrete structure

Life-cycle of concrete

Modern concrete is composed of a mixture of aggregates (65%–80% v/v), cement (10%–12% v/v) and water (14%–21%), and usually includes other constituents such as mineral components (cement extenders/additives) and chemical admixtures (e.g. air-entraining agents, water reducers and accelerators), and occasionally fibres (<1%) (Van Oss & Padovani 2003). Concrete is used in the construction of pre-stressed, reinforced and unreinforced concrete structures. The life-cycle of concrete covers all activities spanning from the extraction and processing of raw/recycled materials to the final decommissioning and demolition of the structure for waste/recycling/reuse of its materials. The scope of studying the life-cycle phases of concrete varies and can be classified into three, as shown in Figure 1. The first phase is the *cradle-to-gate* phase and comprises all relevant processes from raw materials extraction (cradle), manufacturing and processing of the materials and their transportation to the processing plant, within the plant and the batching plant and/or construction site (gate). The *gate-to-grave* phases cover the concrete mixing, construction of the structure, on-site transportation activities, operational phase, demolition of the structure and the disposal of demolished material to a landfill. The final phase, *grave-to-cradle*, refers to end-of-life material recovery strategies that include the recycling and reuse of the demolished materials.

This study gives a comprehensive review of the *cradle-to-gate* environmental impacts of concrete in SA. In summary, the scope of this study includes:

1. Investigating and quantifying raw materials directly consumed in the extraction and manufacture and transportation of materials for concrete production. The review omits the environmental impacts arising from the production of mining machinery and processing of secondary materials such as gypsum.
2. Identifying and quantifying the corresponding CO_2-e emissions generated directly in the extraction, manufacture and transportation of the materials.

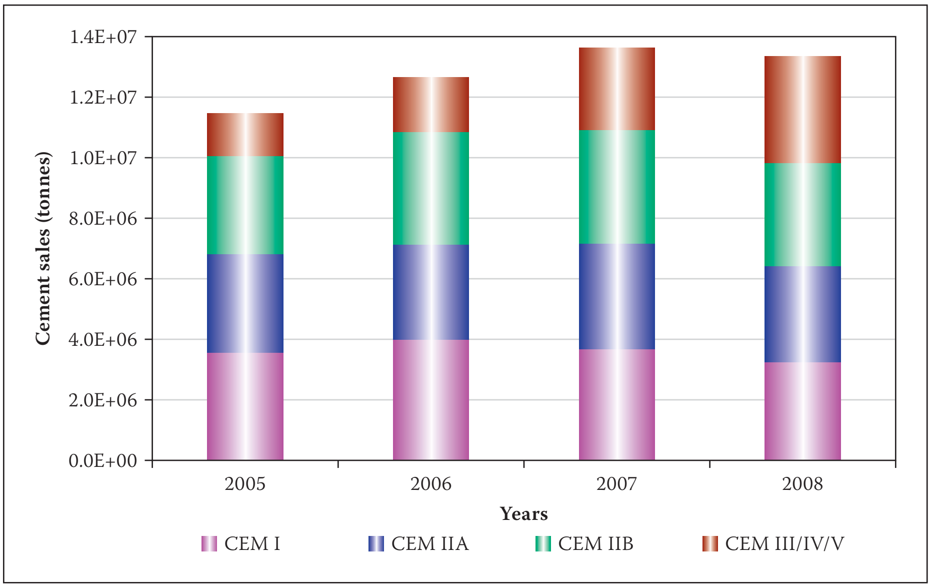

Figure 2 Tonnage of cements produced for the period 2005 to 2008 (C&CI 2008)

3. The data covers a four-year period from 2005 to 2008. The data sources used are specific to South Africa.

ENVIRONMENTAL IMPACTS OF CONCRETE CONSTITUENT MATERIALS

Cement

Portland cement production involves the chemical transformation of raw materials: calcium oxides (63%–69% by mass in cement); silica (19%–24%); alumina (4%–7%) and iron oxide (1%–6%) into various types of cementitious products, by-products and wastes. The Portland cement manufacturing process consists of five main steps:

1. Quarrying of limestone and transportation of raw materials to the processing plant. The mining process involves the use of explosives, while diesel fuel is usually consumed in the transportation of the quarried materials to the processing plant.
2. Preparation of "raw meal" for pyro-processing, whereby, all raw materials (crushed limestone, iron ore, clay or shale) are mixed together in the correct proportions (raw meal homogenisation) and finely ground.
3. Pyro-processing of raw materials to produce Portland cement clinker using the wet or dry process. The latter refers to the process whereby raw materials are first ground and heated before being fed into the kiln, whereas in the wet process, the raw materials are crushed, ground and mixed as slurry. The most efficient dry-process kilns use approximately 2.9 GJ per tonne of clinker (http://www.energy-efficiencyasia.org/docs/industrysectorscement_draftMay05.pdf). Wet-process kilns are more energy intensive and can consume more than twice the amount used by dry-process kilns (Gartner 2004). All cement kilns in SA use the dry process.
4. Final grinding of the clinker together with inter-grinding with a small proportion of gypsum to produce Portland cement. Waste products from, for example, power stations (fly ash), iron/steel manufacturers (blast furnace slag) and others can be used as partial replacements for Portland cement to form blended cement, either by inter-grinding with the clinker, or separate grinding followed by inter-blending.
5. Transportation of the finished product to the consumer in bulk or in bags. Typical transportation distances of the cement to site can vary. This review assumes

a 100 km distance, from literature (McIntyre *et al* 2009).

Total cement production for the period 2005–2008

Cementitious sales in SA are made by a cement industry characterised by four major producers (as of 2009). Other producers are expected to enter the industry in coming years. The term "cementitious products" refers to cements complying with SANS 50197-1 (which corresponds to equivalent EN 197 specifications) and cement extenders sold directly to end users such as ready-mix concrete producers. When considering the four-year average (2005–2008), approximately 20.4 Mt of raw materials per year were used in the production of cementitious materials. On average, 12.8 Mt of binders were produced per year. The binders produced include Portland cement and blended cements such as CEM IIA, CEM IIB, CEM III, CEM IV and CEM V, all produced in accordance with SANS 50197-1. Figure 2 gives the tonnage for each binder produced.

Of the total 12.8 Mt of binders produced per year on average between 2005 and 2008, approximately 37% (4.73 Mt) went towards the direct production of concrete. This figure constitutes 17% ready-mix production, 16% concrete product manufacturers and 4% directly for civil construction works, as shown in Figure 3. The percentage value for concrete production could well be higher than 37% as it does not account for the 55% of cement sales to independent blenders (6%) and cement re-sellers (49%). In addition, a part of the 5% cement sold directly to building construction represents that used in the production of concrete buildings, and another part in mortar-based applications (masonry mortar, plastering and a base/sub-base for flooring). However, to avoid greater inaccuracies in analysis, this review assumes that 37% of all cementitious materials produced in SA went towards concrete production in the years 2005–2008.

Carbon equivalent emissions for cement

The main CO_2-e emissions resulting from cement are due to: (1) calcination or decomposition of limestone ($CaCO_3$) to calcium oxide (CaO), in the process liberating CO_2 and, (2) coal burning in pyro-processing. Secondary sources of CO_2-e emissions arise from the combustion of fossil fuel required to produce the electricity consumed by cement manufacturing operations and from the transport of raw materials and the finished product to consumers (Association of Cementitious Material Producers (ACMP) 2011).

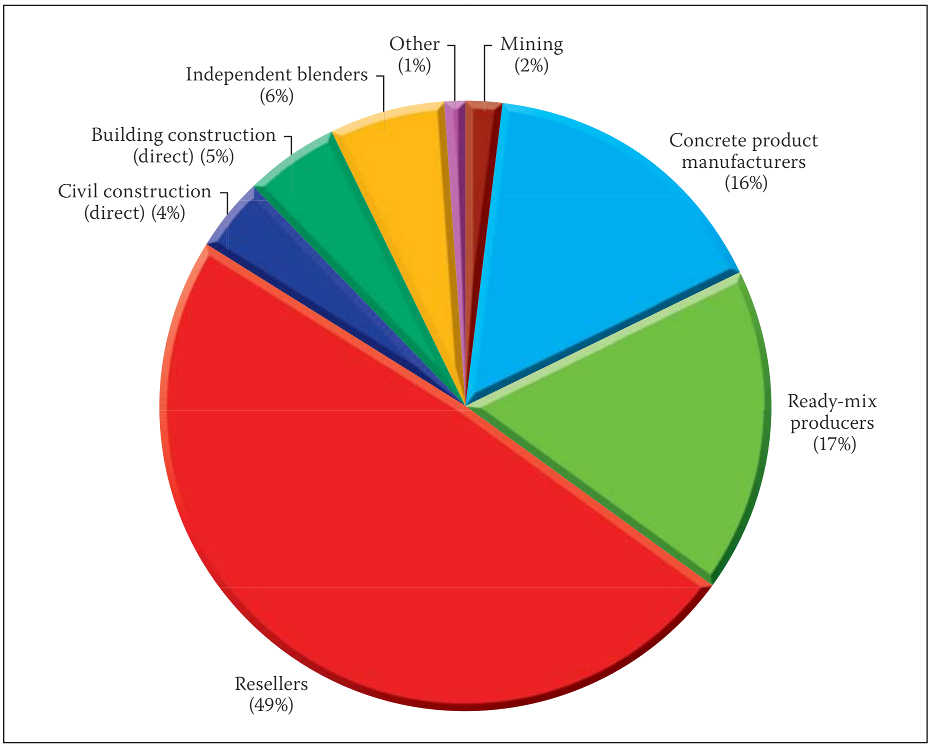

Figure 3 Four-year (2005–2008) average values of the applications of cement in South Africa (C&CI 2008)

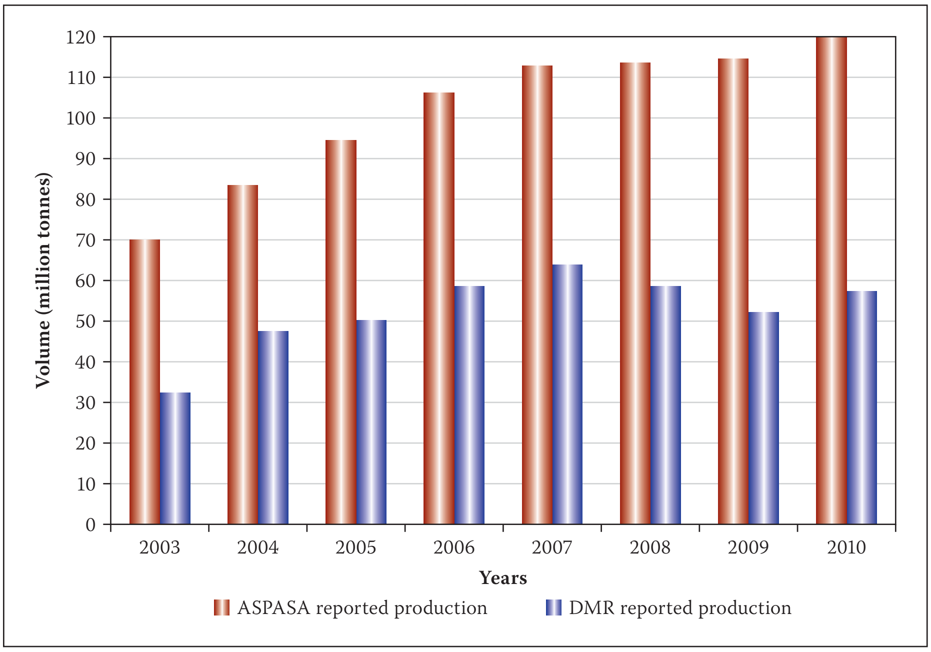

Figure 4 Annual fine and coarse aggregates production, for all uses (e.g. in concrete, road base and sub-base layers, mortar) in South Africa (2003–2010) (Support Programme for Accelerated Infrastructure Development (SPAID) 2008; Kohler 2011)

Table 1 Average total greenhouse gas emissions from cement manufacturing (InEnergy Report 2010)

Year	Cement for concrete production (t)	kg CO_2-e emissions			
		Scope 1	Scope 2	Scope 3	Total emissions (kg CO_2-e)
2005	1.15E+07	9.38E+09	1.67E+09	2.50E+08	1.13E+10
2006	1.27E+07	1.04E+10	1.84E+09	2.76E+08	1.25E+10
2007	1.37E+07	1.12E+10	1.98E+09	2.98E+08	1.35E+10
2008	1.33E+07	1.09E+10	1.94E+09	2.90E+08	1.31E+10
Four-year average kg CO_2-e					1.26E+10
Contribution from the concrete industry (37%) kg CO_2-e					**4.7E+09**

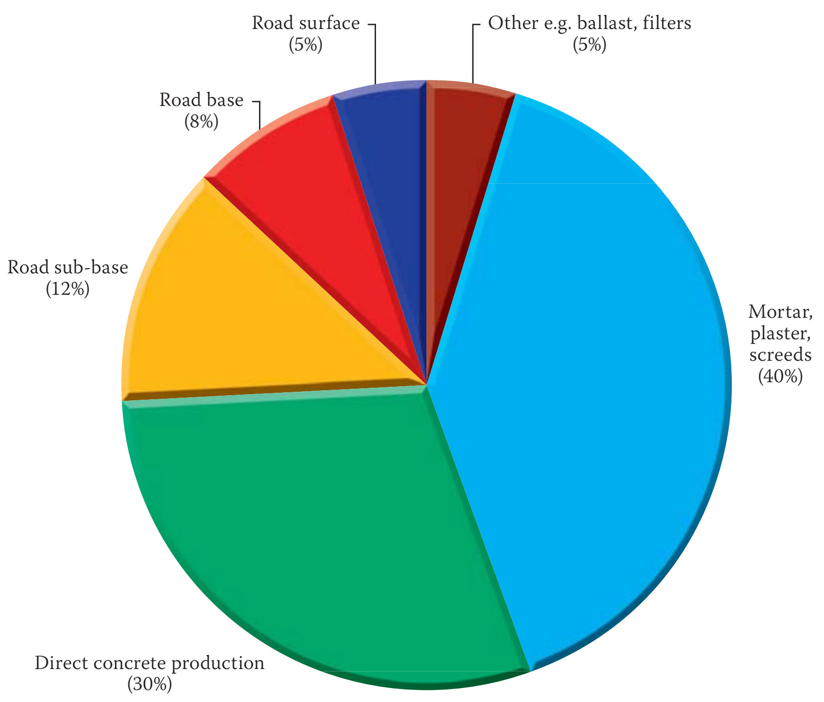

Figure 5 Application of aggregates in construction (Support Programme for Accelerated Infrastructure Development (SPAID) 2008)

Table 2 CO_2-e emissions per tonne of aggregate produced (InEnergy Report 2010)

Activity	Energy source#	Energy MJ/tonne	kg CO_2-e /MJ	kg CO_2-e/ tonne (InEnergy Report 2010)
Quarrying	ANFO[c]	0.045[a]	0.044	0.002
Onsite transportation	Diesel	26.41[a]	0.073	1.928
Crushing, sieving & sorting	Electricity	28.80	0.119	3.43
Transportation to construction site (50 km)[b]	Diesel	38	0.073	2.774
Total		93.3		8.1

a Based on the assumption that diesel oil constitutes 99.9% of the energy and explosives are 0.1% during quarrying
b Typical transportation distances of materials to site; the capacity of the truck is estimated to be 25 t for aggregates (Mclntyre *et al* 2009). No local data available for this assumption.
c ANFO – Ammonium Nitrate Fuel Oil

Existing data on CO_2-e emissions from cement production in SA is available in the InEnergy Report (C&CI 2010)[1]. These emissions are reported in accordance with the World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI) Protocol (which is a methodology for calculating CO_2-e emissions). In the WRI/WBCSD Protocol three sets of emissions from different processes are aggregated to give the specific emissions for a product. The three emissions are categorised as: Scope 1 (direct) emissions which refer to those from raw material calcinations, fuel combustion, site transport of raw materials and personnel, and emissions from explosives detonation at the quarry; Scope 2 (indirect) emissions refer to those from use of purchased electricity; and Scope 3 (other indirect) emissions are those from off-site transportation of raw materials or intermediate products (e.g. clinker).

Based on the assumption that 37% of the cement produced goes into the production of concrete, approximately 4.7 x 10^9 kg CO_2-e are emitted per year as shown in Table 1.

Coarse and fine aggregates

Aggregates – both fine (< 4.75 mm) and coarse (> 4.75 mm – 40 mm) – account for 65%–80% of the volume of concrete. Sources of coarse and fine aggregates can be quarries, alluvial sources such as river sands and gravels, or recycled industrial waste (e.g. mineralogical sands, foundry sands, metallurgical wastes and construction and demolition wastes, etc). Presently, natural resources, such as gravel and sand pits and rock quarries, provide the main sources for aggregates and raw materials for concrete production in SA, with coarse aggregates being totally sourced from crushed rock. In addition, there is limited use of recycled aggregate mainly for pavement base construction (Kutegeza & Alexander 2004). Though not stated in local studies, the main hindrances to the use of recycled aggregates for structural applications are that the recycling facilities and equipment require a high cost of investment (Tam 2009). In addition, there is lack of regulatory requirements (e.g. policies and strategies) on concrete recycling that seek to coordinate various stakeholders (e.g. client, contractor) in the management of construction and demolition waste. Other than the waste management aspects, recycled aggregates in concrete have been shown to exhibit a large variability in their quality, especially when they are sourced from different sites. This variability can, however, be lowered by using site-based recycling. Local data on the mechanical strength and durability characteristics of the use of recycled aggregates in concrete is contained in Kutegeza & Alexander (2004) and Olorunsogo & Padayachee (2002). However, the existing local standards and codes for design of concrete structures (e.g. SANS 10100-1:2000) do not make provision for the use of recycled aggregates in concrete, hence designers may not be willing to specify for these in the design.

Total aggregates produced

There is conflicting data on the total production of aggregate and sand in South Africa, reported by the Aggregate and Stone Producers Association of South Africa (ASPASA) and the Department of Mineral Resources (DMR). ASPASA reported that in 2008 the aggregate sector in South Africa quarried 114 Mt of aggregate and sand, while industry sales reported by the DMR totalled approximately 50% of the ASPASA figures, as illustrated in Figure 4. Sales reported by the DMR cover only those reported by registered operating quarries and sand extraction operators in SA (SUDEO IBC 2007). Estimates made by ASPASA are based on average conversion factors used from cementitious sales that go into the production of concrete.

It is estimated that 30% of aggregate and sand produced in SA (an average of 32.1 Mt for 2005– 2008, based on ASPASA production figures) is used for concrete production, which includes on-site production of concrete and production by ready-mix producers and concrete product manufacturers (CPM). The remainder of the total aggregate and sand sales is used in non-concrete products, e.g. track ballast for railways, and by the water industry for filters in treatment works. Figure 5 shows the application of aggregates in construction.

Carbon-equivalent emissions from aggregates

There is no readily available local energy and emissions data distinguishing the impact of the production of natural quarried fine aggregates from that of coarse aggregates. Extracting and processing a tonne of both fine and coarse aggregates generates an average 8.1 kg of CO_2-e (InEnergy Report 2010) as shown in Table 2.

Table 3 gives the total amount of CO_2-e emissions generated in the production of aggregates for concrete for 2005 to 2008, based on the ASPASA data given in Figure 4.

The amount of fine and coarse aggregates used in concrete production has steadily increased over the four-year period (2005–2008). An average of 32.1 Mt of aggregates used in concrete production led to the consumption of 3.0 x 10^6 GJ of energy and 260 x 10^6 kg CO_2-e emissions.

Table 3 Environmental impacts of aggregates for concrete during the period 2005–2008

Year / Units	Amount of fine and coarse aggregates consumed in concrete production in SA based on ASPASA data	Total kg CO_2-e emissions
	Tonnes	kg CO_2-e
2005	28.4×10^6	230×10^6
2006	31.9×10^6	258×10^6
2007	33.9×10^6	275×10^6
2008	34.1×10^6	276×10^6
Average	32.1×10^6	260×10^6

ASPASA – Aggregates and Stone Producers Association of South Africa

KEY FINDINGS ON RESOURCE USE AND EMISSIONS IN THE CONCRETE INDUSTRY

Raw materials for concrete production in South Africa

On average 39.7 million tonnes of raw materials per year were used for concrete production in SA for the period 2005–2008. Of these, 32.1 Mt were coarse and fine aggregates and 7.6 Mt were raw materials (limestone, silica, iron ore and clay used in the production of 4.73 Mt of binders). On average, coarse and fine aggregates account for 61% by mass of the total raw materials consumed per year in concrete production.

Carbon-equivalent emissions generated

The dependence on non-renewable energy resources (e.g. coal) in the manufacturing of constituent materials for concrete in SA has led to the production of global greenhouse gas (GHG) emissions. An average of 49.2 x 10^8 kg CO_2-e emissions per year were emitted in SA for the period 2005 to 2008. These CO_2-e emissions per annum relate to the *cradle-to-gate* activities for cement and aggregates used for concrete production.

Cement is the main contributor of CO_2-e emissions, contributing on average 94.7% of the total emissions by the concrete industry in SA.

Concrete production in South Africa

Based on Figure 3, an average of 8.69 million m^3 (20.9 Mt) of ready-mix concrete[2] was produced per year for the period 2005–2008. Also, 8.17 million m^3 (19.6 Mt) of concrete was used in the production of concrete products: paving blocks, roof tiles, masonry, floor slabs, retaining blocks and infrastructure products. In addition, 2.04 million m^3 (4.9 Mt) was used in civil engineering construction. In total an average of 18.9 million m^3 of concrete (45.4 Mt) was produced in SA per annum for the period 2005–2008. These amounts are expected to increase in future due to government and private industry investment in new (and replacement) construction to cope with the rapid rate of urbanisation and population growth

When compared to the worldwide consumption of concrete, SA produces only 0.58% of the estimated 12 billion m^3 (CEMBUREAU, 2009). However, the latter worldwide estimate of concrete is based on the assumption that all world cementitious products go towards the production of concrete.

Solutions to reducing the environmental impacts of the concrete industry

Coarse and fine aggregates account for 61% of the total raw materials, by mass, consumed per year in concrete production in SA. To reduce the use of primary aggregates in concrete, the Waste Management Act (2008) in SA provides incentives that encourage the use of alternative materials, such as recycled aggregates. Substituting primary aggregates with recycled aggregates, where it is technically feasible, allows for current levels of demand for aggregates to be met while conserving primary aggregates, and consequently reduces pressure on existing landfills. However, the major limitation to the use of recycled aggregates in concrete in SA is the lack of design provisions for the use of recycled aggregates in concrete in current standards and codes (e.g. SANS 10100-1:2000). Also, while some work has been done on the use of recycled aggregates in concrete (e.g. Kutegeza & Alexander 2004), considerably more research is required in this area to give confidence in the use of these materials. Hence, designers are generally not willing to specify for this in design.

In addition to legislative measures and design code provisions for recycled aggregates, economic instruments such as taxes and charges are possible interventions which can be put in place to minimise the consumption of primary aggregates. For example, countries such as the UK and Denmark have introduced an aggregate levy. The UK levy imposes a tax of £2.10 per tonne of quarried aggregates (2010 figure) for primary extraction of aggregates and on landfill disposal (Aggregates Levy 2002). The tax is expected to bring about a greater efficiency in the use of primary aggregates and greater use of alternative materials. However, the possible introduction and implementation of a similar levy in SA is currently impossible, due to the reported disaggregation of the sand and aggregate industry. This disaggregation is evidenced by the significant difference in data on the production of aggregates as reported by both ASPASA and the DMR.

Cement is the main contributor of CO_2-e emissions, contributing on average 94.7% of the total emissions by the concrete industry in SA. Techniques to reduce the CO_2-e emissions of cement can be found in literature (Damtoft *et al* 2008; Gartner 2004) and include:

(a) **Improved thermal and electrical energy efficiency of cement kilns:** Optimising kiln processes and plant efficiencies during cement production results in the reduction of CO_2-e emissions and also brings down the cost of production. All the cement kilns in SA use the dry processing of raw materials, which is more energy efficient than the wet process.

(b) **Co-processing of alternative fuels:** Substituting wastes for raw materials is referred to as co-processing alternative fuels and raw materials (Ziegler *et al* 2007). Substituting wastes such as waste tyres and biofuels for primary fuels (e.g. coal) can help reduce CO_2-e emissions associated with burning the fuels. SA has accepted the co-processing of waste in cement kilns as best practice under the Waste Incineration Directive 2000/76-EC. Previously, co-processing of wastes in cement kilns met with opposition from local communities and environmental organisations. Communication to public representatives about the opportunities and potential benefits of co-processing is required. For example, the use of waste fuels presents a number of benefits: it increases the capacity to divert landfill wastes, reduces the energy intensity of fossil fuels consumption, reduces carbon emissions, and creates jobs (e.g. sorting of wastes).

(c) Reducing the clinker content in cementitious materials:
Blended cements are produced by intergrinding Portland cement clinker with supplementary cementitious materials (SCMs) or by blending Portland cement with SCMs such as fly ash from coal combustion in electricity-producing plants, or blast furnace slag from iron plants. The blended cements produced should comply with provisions of SANS 50197-1, SAN 50413-1 and SANS 1491 parts 1, 2 and 3. The use of blended cements reduces the amount of clinker that needs to be produced, lowers the CO_2-e emissions, and diverts waste from landfills, as SCMs are by-products of other industries that would otherwise have ended up being disposed.

Figure 2 shows that between 2005 and 2008 there was a growth in demand of blended cements: CEM III/CEM IV/CEM V, whereas the demand for CEM I Portland cement reduced. This has a positive impact on the reduction of the CO_2-e emissions of the concrete industry in South Africa.

CONCLUSION

The purpose of this study was to evaluate the extent of resource use and emissions associated with the production of concrete construction materials in South Africa. Four-year average (2005–2008) data was provided for resources consumed, energy consumed and wastes emitted to the air due to the quarrying and processing of raw materials for concrete in SA. From the study it was determined that, on average, 39.7 Mt of raw materials per year are used for concrete production. Of these, 32.1 Mt were coarse and fine aggregates and 7.6 Mt raw materials (limestone, silica, iron ore and clay used in the production of 4.73 Mt of binders). For the same period, an average of 49.2×10^8 kg CO_2-e emissions per annum was emitted during the extraction, production and transportation of constituent materials for concrete. Cement is the main contributor of CO_2-e emissions, contributing on average 94.7% of the total emissions by the concrete industry in SA.

In addition to policy instruments such as carbon taxes, there are a number of techniques to reduce the CO_2-e emissions and energy use of the cement industry. These include: improving the energy efficiency of cement kilns, co-processing of alternative fuels in cement kilns and reducing the clinker/cement ratio by substituting part of the clinker with SCMs.

In total an average 18.9 million m^3 of concrete (45.4 Mt) was produced in SA per annum for the period 2005–2008. This amount is only 0.58% of the estimated 12 billion m^3 of concrete produced worldwide. However, it was noted that, based on the continued government and private industry investment in new (and replacement) construction to cope with the rapid rate of urbanisation and population growth, these values are expected to rise in future. This shows the need to involve everyone associated with the life-cycle of a concrete structure to further reduce the overall burden of concrete structures.

NOTES

1 InEnergy report contains CO_2-e data on the cradle-to-gate phase of concrete constituents and concrete products in South Africa.

2 The consumption of concrete is based on cement sales figures. The calculations are based on the assumption that on average 250 kg of cement is used to produce 1 m^3 of concrete. Thus, the yearly amount of ready-mix concrete produced in SA is

$$\frac{17\% \times 12.8 \times 10^9\ kg}{250\ kg/m^3} = 8.7 \text{ million m}^3.$$

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