Material Flow Analysis of Concrete in the United States

by

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ABSTRACT

Concrete is the second most consumed material in the world after water. Due to the sheer mass of concrete consumed annually and its associated resource and environmental impacts, improving the materials management of concrete consumption is a critical problem in the United States. It is increasingly evident that the society lacks knowledge of the collective material composition of the urban environment—of how we produce, consume and dispose of concrete. This thesis argues that the lack of informational linkages is driving the individual approaches of the construction industry, policy makers, environmental agencies and waste management industry, which results in the current segregated and government-subsidized material management. In order to identify opportunities for more effective materials management, this thesis performs the first comprehensive Material Flow Analysis for concrete in the United States for the year of 1996 to identify opportunities for more effective materials management. The dominant concrete products and the end-use categories in the United States are identified. The associated water, energy and fuel consumption and emissions produced are also incorporated. Five lifecycle stages are covered: (i) extraction of raw materials, (ii) cement manufacturing, (iii) production, (iv) use and (v) waste management of concrete. Two untapped material management opportunities are identified: minimizing water consumption during the extraction stage and the off-site production stage. In addition, three key observations are made: (i) the energy efficiency of the cement industry in the United States is close to saturation, (ii) product choice and concrete design are dominant factors for a more responsible materials consumption approach, and (iii) demand-side management is recommended as a more optimal approach than recycling in dealing with the current construction trends in the United States.

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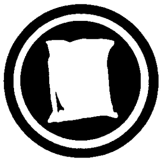
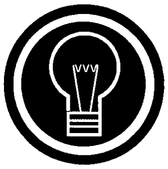
LEGEND

These symbols are used throughout the Material and Energy Flow Analysis. Waste materials and waste water are in gray.

Materials (solid)	
Water	
Energy	
Fuel	
Emissions	

In addition, the Empire State building is often used as a physical representation of a mass unit. It is a 106-story skyscraper constructed partly from 47,420 m^3 or 0.1 million metric tons (Mt) of concrete.

CHAPTER 1 INTRODUCTION

1.1 Introduction

Concrete, as the second most consumed material in the world after water[1], serves as a vital building material for the infrastructural needs of most societies. Its ubiquitous use in buildings, highways, bridges, airports, dams and water treatment plants continues to grow worldwide. In addition, cement, an essential ingredient of concrete, provides important applications as soil cement for slope protection and ditch lining and as a waste and contaminant stabilizer. However, cement manufacturing produces 3-8% of global CO_2 emissions (World Resources Institute, 1995; World Business Council of Sustainable Development, 2002; ATHENA SMI, 1999 cited in Chaturvedi, 2004; Mehta, 1998). Moreover, the cement industry is highly energy-intensive. In 2000, cement consumed three times more energy than steel on a per dollar output basis[2] (EIA, 2002). For the same year, at least 16 million metric tons (Mt) of water was used in cement manufacturing alone—not including the water required for raw materials extraction and cement hydration in concrete plants.

Due to the sheer mass consumed annually, the material management of concrete throughout its life cycle is a topic of interest. The lack of informational linkages between the construction industry, policy makers, environmental agencies and waste management industry, current material management approaches have been reductionistic in nature. As a result, the current means of production, use and management of concrete and other building materials have either been segregated, exorbitantly expensive and/or government-subsidized. This thesis performs a Material Flow Analysis (MFA) of concrete in the United States for the year 1996 to identify material management opportunities by bridging the informational linkages between the relevant actors. Though MFAs have been conducted for construction minerals (McEvoy et al, 2004 for U.K.) and for waste concrete (Kelly/USGS, 1998), this is the first attempt to capture the entire life cycle of concrete flows in the United States.

The next section describes the current status of concrete consumption and production, with emphasis on the United States, as background information. Following that, the current lack of information linkages between the relevant actors is identified and the problem statement and objectives of this thesis are defined. Lastly, the conclusions of this chapter are presented.

1.2 Concrete as a building material

Concrete is made from mixing cement, aggregates and water in a typical composition as shown in Figure 1.1. In essence, cement reacts with water to form a binder for the aggregates to form concrete. Predecessor forms of Portland cement were first used by the

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[1] Sedgwick 1991 cited in Brand 1994.

[2] For delivered energy. Based on 1992 dollars. See Figure 1.5.

Romans around 1500 BC. In 1824, Portland cement was patented in England and its use has since flourished worldwide. Today, nearly three metric tons of concrete[3] is poured for every person in the world each year. This figure is expected to grow since the global consumption of cement has been exponentially increasing for the past few decades (see Figure 1.2).

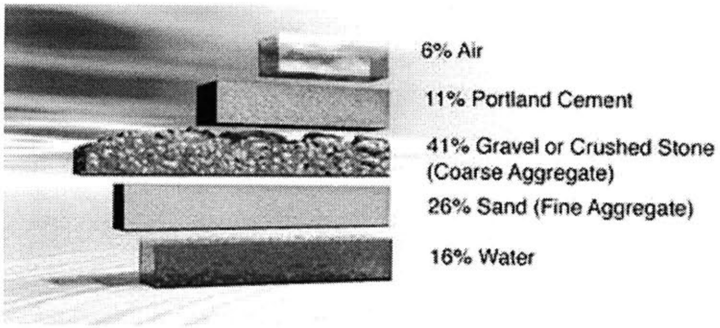

Figure 1.1 Typical composition of concrete by volume
(Source: Portland Cement Association: http://www.cement.org/basics/concretebasics_concretebasics.asp)

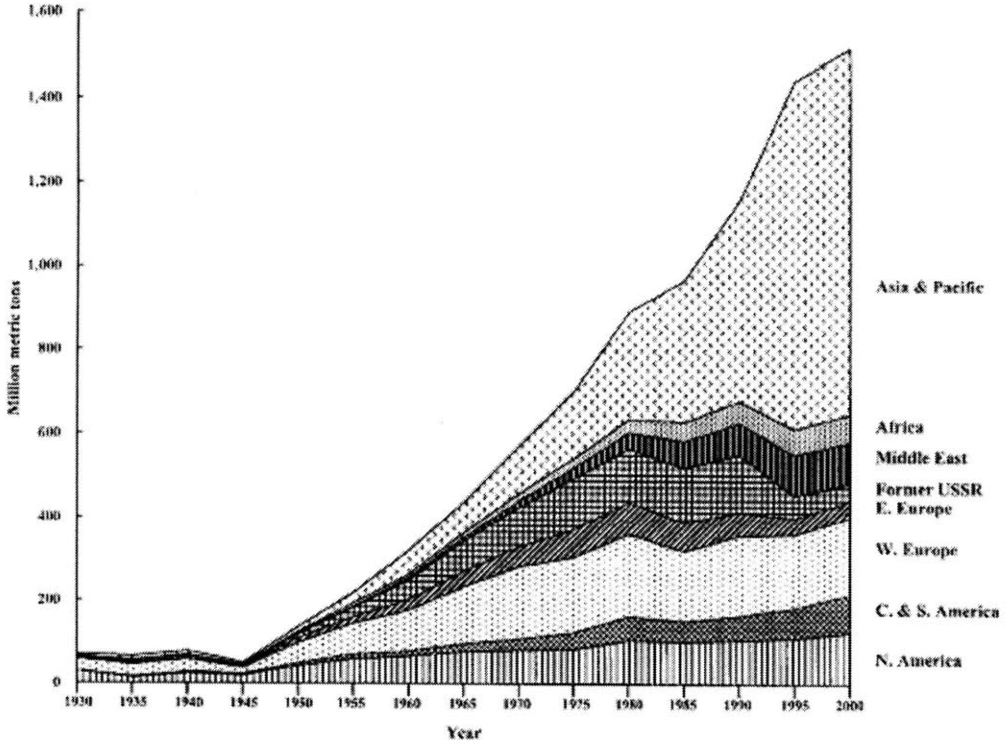

Figure 1.2 Global consumption of cement by region (1930 – 2000)
(Source: van Oss and Padovani, 2002)

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[3] Computed from USGS Cement MYB, also verified with Klee/World Business Council for Sustainable Development (2003).

In the United States, concrete has been the most dominant building material since the late 1930s (Fernandez, 2004). In 2000, concrete consumption was at 400 Mt, at least one order of magnitude larger than the consumption of wood at around 125 Mt and steel at an estimated 63 Mt (see Figure 1.3; Fernandez, 2004). From the same figure, the concrete consumption is expected to double to 800 Mt by 2050 (Fernandez, 2004). In general, the upward trends in building materials consumption in the United States are driven by an increase in average size of new home per capita[4] (National Association of Home Builders, 2004 cited in Fox, 2005) and an increase in second-home ownership[5] (National Association of Realtors, 2004 cited in Fox, 2005).

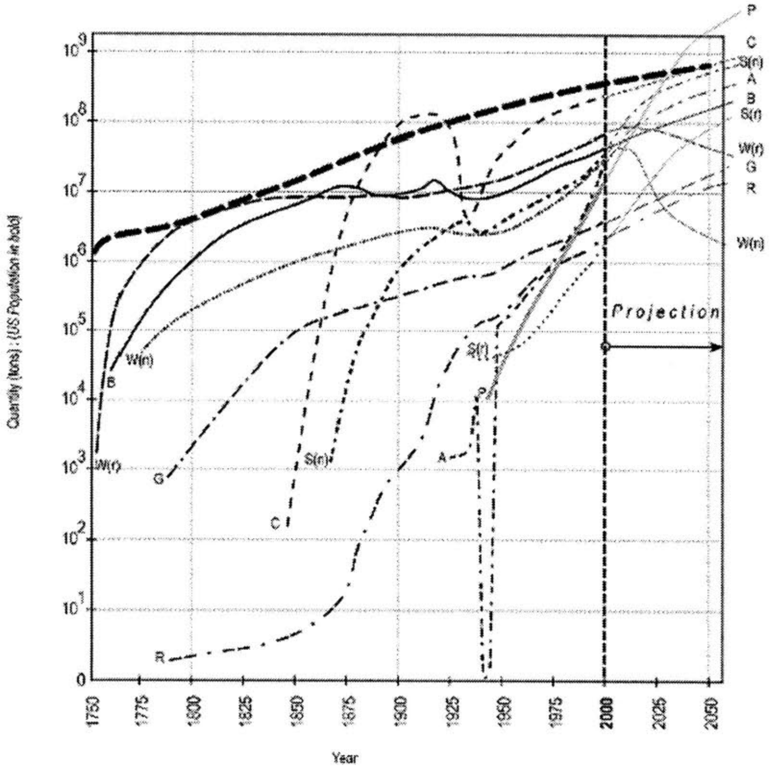

Figure 1.3: Consumption of building materials in the United States from 1750 – 2050
(Source: Fernandez 2004; Moavenzadeh ed. 1990)

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[4] Since 1950, the average new house has increased by 1,247 square feet while the average household size has decreased by 1 person.

[5] Since 2001, there is a 24% increase in the number of Americans with second homes.

Five aspects of concrete consumption and production are identified to be of concern in the context of material management. They are (i) resource consumption, (ii) water consumption, (iii) energy consumption, (iv) carbon dioxide emissions and (v) construction and demolition waste generation. Each aspect is discussed in the following section.

(i) Resource consumption

The extraction of aggregates, which make up 70% of concrete by volume, is associated with concrete production. Globally, almost 3 Gt (Giga metric tons or 10^9 metric tons) of nonfuel raw materials is consumed in cement manufacturing annually (van Oss and Padovani, 2003). The cement production of the United States has been increasing 0.7% per year between 1970 and 1997 (Martin et al, 1999). This signals a parallel increase in aggregates consumption and concrete production. The increase is a major factor for the surge of aggregates or construction materials (sand, gravel and crushed stone) consumed (see Figure 1.4.) In 1900, 33% of the total non-energy materials (or non-energy carriers) used was for construction materials and by 1998, it had ballooned to 70-73% (Horvath, 2004; U.S. Dep. Interagency Working Group, 1999; Matos and Wagner, USGS, 1998).

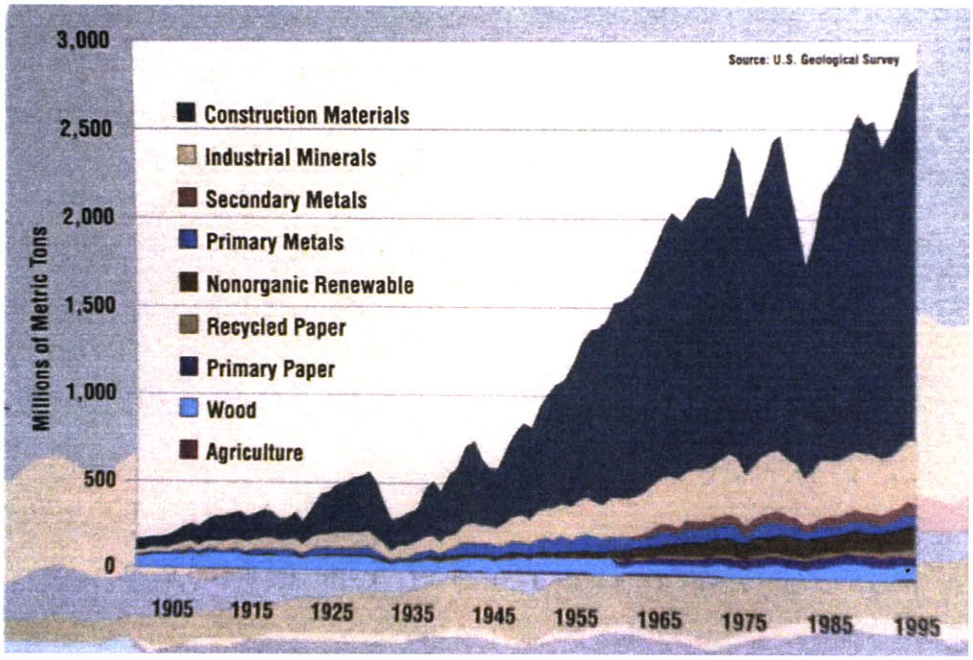

Figure 1.4: Total raw materials use in the United States (1900 – 1995)
(Source: U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flows, 1999; Matos and Wagner, USGS, 1998)

(ii) Water consumption

Water is consumed in the processing stages during the extraction of raw materials and cement manufacturing and concrete production. In addition, mix water is required for cement hydration, a process where the cement reacts with water to form a binder for the aggregates. Van Oss and Padovani (2003) estimated that the current annual worldwide water consumption for cement hydration is approximately one Gt of water. In the United States, at least 16 million metric tons (Mt) of water was used in 2000 for cement manufacturing alone. This is analogous to supplying water for at least 230,000 Americans for an entire year.

(iii) Energy consumption

The United States Energy Information Administration (EIA) estimates that approximately 400 PJ (400 x 10^{15} J) is consumed by the cement industry annually. Figure 1.5 shows the delivered energy across various industries. In 2000, cement consumed three times more delivered energy than steel on a per dollar output basis (EIA, 2002.) This ratio is likely to increase if primary energy is used as a comparison instead. The majority of the energy is expended by the pyroprocessing process, where the raw materials (e.g. limestone, clay and iron ores) are combusted at 1,400°C in rotary kilns to form clinker, an intermediate compound of cement.

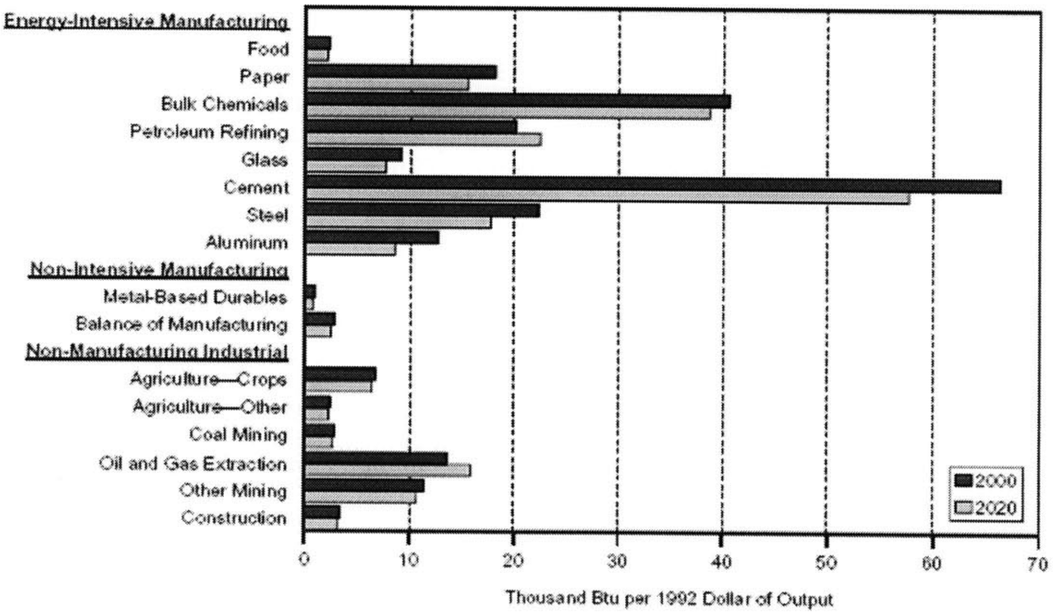

Figure 1.5 Delivered energy consumption per unit of output by industry group, 2000 and 2020
(Source: Energy Information Administration, *Annual Energy Outlook 2002,* DOE/EIA-0383 (2002), Washington, DC, December 2001 cited in Uruh/EIA, 2002.)

(iv) Carbon dioxide emissions

Clinkerization is the main pyroprocessing process of cement manufacturing, where CO_2 is emitted from the thermal decomposition of limestone (an essential source of calcium compounds for cement). Given that approximately one metric ton of CO_2 is released for every ton of cement produced, cement manufacturing is put in the forefront for producing for 3-8% of global CO_2 emissions (Chaturvedi, 2004; World Resources Institute, 2004; ATHENA SMI, 1999, World Council of Sustainable Development, 2002, Mehta, 1998). The global CO_2 emissions distribution is shown in Figure 1.6.

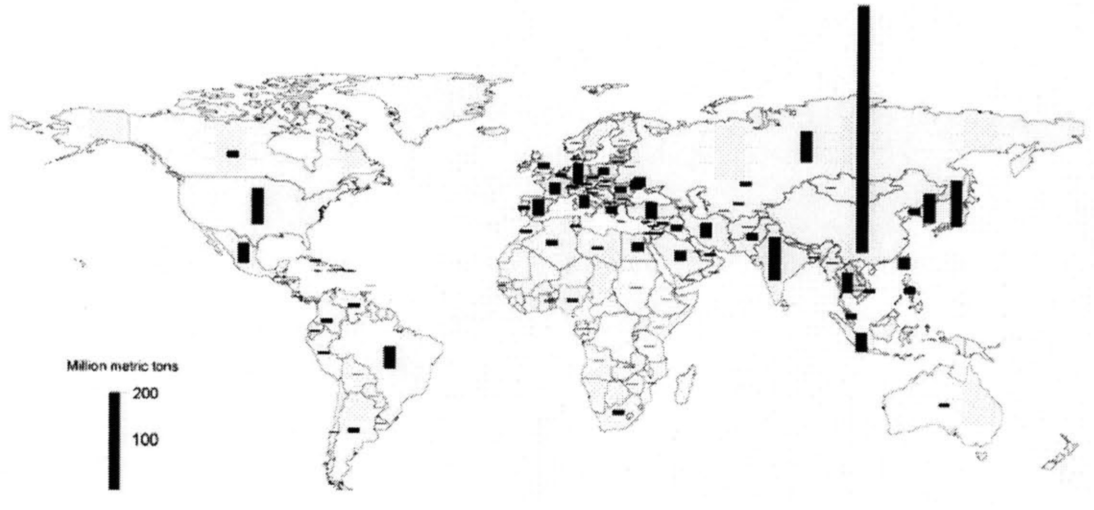

Figure 1.6 Global CO_2 emissions from cement manufacturing (mid 1990s)
(Source: van Oss and Padovani 2002)

(v) Construction and demolition waste generation

In the United States, concrete accounts for 40-50% of construction and demolition (C&D) waste generated from buildings annually (Sandler, 2003). Given that 123 Mt of building-related C&D debris is produced annually (Franklin/EPA, 1998), approximately 50 – 60 Mt of waste concrete have to be landfilled or recycled from buildings alone. The actual figure of waste concrete generated is closer to 180 Mt when C&D waste from highway, roads, bridge and other public works are included (Turley, 2002 cited in EPA, 2003). In 1994, there were 1,900 active C&D landfills in the United States (Franklin/EPA, 1998) for the depositing of such massive inert volumes of concrete. Over time, the number of landfills is increasing due to a projected surge in demand of concrete and other building materials in the United States.

1.3 The lack of informational linkages

In the construction industry, materials use represents different things to the relevant actors. As building material users, engineers and architects have fairly sophisticated knowledge of the physical, thermal and chemical properties of commonly used structural materials, namely concrete and steel. The understanding of these properties allow for cost-effective and functional designs of buildings, highways, bridges and other structures. On the other hand, building material manufacturers and mining companies are concerned with using cost-effective combinations of resources and industrial conditions to tap into new markets for their products. Policy-makers, environmental agencies and waste management industry form the third group of actors. Their objective is to dispose of waste materials through economically viable means with minimal impact on the environment, through landfills, incineration or recycling. To fulfill the needs of society, the construction industry, policy makers, environmental agencies and waste management industry act together to produce and manage the enormous quantities of building materials demanded.

Despite the long history of the construction industry, interactions of the relevant actors and materials in the urban environment remain unclear. In the United States, we have little or no knowledge of the collective material composition of the physical artifacts in the urban environment—of how concrete and other building materials are produced, consumed and disposed of. This thesis argues that the lack of informational linkages between material use and resource use, supply and demand dynamics, and waste production is a key cause of reductionist approaches being adopted by the construction industry, policy makers, environmental agencies and waste management industry. In viewing the urban environment as an organizational unit, such approaches have resulted in an unsuspectingly chaotic pattern of material flows which are managed by exorbitantly expensive, inefficient and government-subsidized means. In the following, the disconnections are pointed out the current information provided by each type of actors, namely the (i) concrete-related manufacturers, (ii) concrete users and (iii) policy-makers and waste management personnel.

(i) Concrete-related manufacturers

This group covers the raw material extraction industry, cement producers and concrete producers. The United States Geological Survey (USGS) documents the quantities of raw materials mined to produce cement (e.g. limestone, clay and iron ore) and concrete (sand, gravel and crushed stone), along with associated solid waste produced in annual Mineral Commodities Summaries (MCS) and Mineral Yearbooks (MYB). The use of resources by cement and concrete production is well-illustrated in Figure 1.4. Though it is known that aggregates make up about 70% of concrete by volume, the relationship between the quantity of construction materials extracted and the quantity of cement and concrete produced for the same time period is not intuitive. In addition, no linkage is established with the associated solid waste (mining soils, waste rock, mill tailings), overburden (earth removed for the extraction of underlying ores), water use, emissions and other pollution.

Linkages are also missing in the cement industry, even though its energy use and gaseous emissions are extensively tracked. The United States Energy Information Administration (EIA) provides data on energy consumption and greenhouse gas emissions of major energy-intensive industries in the Annual Energy Review reports and carbon dioxide (CO_2) emitted by the cement industry annually. On a positive note, an EIA report showed that the building industry consumes ~13% of the energy demand in the United States, from building material production and building demolition alone (estimated from data from EIA, 2004 as cited in Billington et al, 2004). Such a knowledge base has helped the cement industry to strive for and implement more energy-efficient technologies[6] and use alternative waste fuels such as tires and waste solvents. The cement industry has taken a strong stance to relate the means of managing energy use with cement production. Moreover, the U.S. cement industry is increasing its production of blended cements, which contain supplementary cementitious materials (SCM) such as fly ash and other industrial and agricultural waste products in order to reduce CO_2 emissions.

The gap in information flow is further compounded by the inherently enormous supply chain of the construction industry. The industry is a major economic powerhouse in the United States, contributing a sizeable portion of the Gross Domestic Product (GDP). The GDP of the construction industry in the U.S. is greater than the GDP of 212 out of the 231 countries in the world (U.S. Census Bureau, 2002 cited in Horvath, 2004). In 2000, the industry was composed of 700,000 establishments, which employed 6.6 million paid employees (U.S. Census Bureau, 2002 cited in Horvath, 2004). Another factor is that the construction industry has historically been fragmented and is very conservative due to liabilities and large amounts of investment and time involved. Understandably, information sharing is simply not encouraged beyond proprietary comforts.

(ii) Concrete users

Concrete users include engineers, architects and the public. To engineers and architects, the versatility and durability of concrete makes it an excellent selection for designing and building physical structures—buildings, bridges, roads, airports, dams, wastewater treatment plants, etc. While engineers and architects are well-versed in designing with building materials, the linkages between the environmental impacts of the building materials they specify for in the construction plans or the fate of the materials after demolition are hardly established in the mainstream literature, let alone discussed. However, this trend is gradually changing through education, albeit slowly.

Today, concrete is used ubiquitously in homes and workplaces—as concrete walls, beams, floor slabs, foundations, exterior envelope, garages, decks and roads. Ironically, its use in the urban landscape is too commonplace for any person to appreciate both the embodied energy of building materials and the resource value (and not the depreciated investment value) of buildings.

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[6] See research conducted by the Lawrence Berkeley National Lab for the cement industry (Worrell et al 1999)

(iii) Policy-makers and waste management personnel
In order to deal with the increasing volume of construction and demolition (C&D) waste, policy makers have been proposing bans in landfills and higher landfill taxes to encourage recycling and to promote the use of secondary materials as construction materials.

In addition, the U.S. Environmental Protection Agency (EPA) has been actively supporting waste management proposals. However, grounds for establishing linkages between the generation of concrete waste (or building material waste) and the current stock of physical infrastructure have been weak. Little information on C&D waste generation has existed for the past three decades until the recent 1998 'Characterization of Building-related Construction and Demolition Waste' publication which examines only building-related C&D waste and does not include waste from highways and other public works (Franklin/EPA, 1998).

While small quantities of concrete are not toxic, pouring 400 Mt of a single material into the urban environment every year is unprecedented and it deserves greater attention from researchers and policy makers. The bulkiness of concrete at a density of 2,300 kg/m^3 makes it both technically difficult and costly to manage. Furthermore, the current reductionist approaches of the actors result in segregated efforts which, instead of dealing with materials use, divert the consequences of material use.

1.4 Problem statement and objectives

It is difficult to establish linkages between material use and resource use, supply and demand dynamics and waste production for multiple groups of actors to work more synergistically along the production chain. The culmination of consequences has crystallized in these recent trends:

1. *Distorted demand for natural aggregates from decreasing local reserves*
   Aggregate consumption for concrete production and aggregate availability has not been well-correlated. Cement imports, among other commodities, are also getting more competitive since China and other countries are drastically expanding their physical infrastructure[7].
2. *Continued reliance on coal for cement manufacturing*
   A less carbon-intensive fuel mix is more efficient in minimizing emissions than implementing energy-efficient technologies.
3. *Slow progress of the construction industry to examine its ecological footprint* compared to the paper, chemical, electronics and automobile industries
4. *Reliance on end-of-pipe waste management solutions* which divert millions of cubic meters of waste concrete instead of using source reduction strategies

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[7] The United States has experienced cement shortages due to China's consumption and use of barge transportation (PCA 'The Monitor: Flash Report,' 2004.)

5. *Understated importance of design for flexibility and deconstruction* to delay demolition and facilitate recycling of concrete and other building materials among engineers and architects
6. *The value of regular maintenance of physical structures* is frequently dismissed as a worthwhile investment in the long run[8]
7. *Technologies focusing on 'intelligent' buildings and specialized concrete but not on minimizing material use or increasing efficiency of reusing/recycling concrete*
8. *Lack of accountability for the consequences of resource use* associated with concrete production

To increase transparency in the concrete industry, this thesis advocates for the documentation of associated material flows of concrete production to create an informative picture to open dialogue between the different actors. This leads to the formulation of the following problem statement:

This thesis produces a Material Flow Analysis of concrete in the United States in 1996 to identify opportunities for more effective materials management.

Three main objectives are identified:

(1) To clearly define the lifecycle of concrete from the extraction of raw materials stage to waste management stage;
(2) To identify the dominant concrete products and end-use categories during the use of concrete and the end-uses of recycled concrete; and
(3) To perform a comprehensive set of associated material, water, energy and emissions flows for the lifecycle of concrete

The completed Material Flow Analysis could be used to formulate new collaborations and streamlining of processes. With a more realistic representation of concrete production:

1. the continuity and relevance of the different life cycle stages of concrete (extraction of raw materials, production, use and disposal stages) become more succinct and informative for relevant parties;
2. the increased understanding of each role's significance could aid the players in evaluating the impacts of their decisions on other upstream and downstream actors; and
3. the colossal scale of concrete consumption and the relative time scale of the physical structures in the urban environment could be grasped to inform design decisions

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[8] The American Society of Civil Engineers gave the physical infrastructure in the United States an average grade of D and estimated an investment of $1.6 trillion is needed to repair and rehabilitate the neglected infrastructure (ASCE 2005 Report Card for America's Infrastructure, http://www.asce.org/reportcard/2005/index.cfm).

1.5 Conclusions

This thesis argues that improving the materials management of concrete consumption is highly critical in the United States due to the sheer mass of concrete consumed annually and associated resource and environmental impacts. Five types of resource and environmental impacts have been described: (i) resource consumption, (ii) water consumption, (iii) energy consumption, (iv) carbon dioxide emissions and (v) construction and demolition waste generation. In addition, the lack of informational linkages driving the reductionist approaches of the relevant actors is evaluated through a review of current information provided by the three main groups of actors: (i) concrete-related manufacturers, (ii) concrete users and (iii) policy-makers and waste management personnel. Next, the problem statement and objectives of the thesis are formulated. This thesis aims to perform the first Material Flow Analysis of concrete in the United States for the year of 1996 to identify opportunities for more effective materials management.

In addition, the overall structure of the thesis is in four main sections: (i) introduction, (ii) MFA results, (iii) discussion and (iv) future work. Chapters 1 and 2 introduce the problem and the methodology used, together with a literature review. The next five chapters present the results of the MFA for each life cycle stage, which provide insight to the linkages between concrete consumption with resource use, demand and supply dynamics and waste management. Namely, they are Chapter 3: Extraction of raw materials; Chapter 4: Manufacturing of cement; Chapter 5: Off-site production of concrete; Chapter 6: Use of concrete; and Chapter 7: Waste management of concrete. The final two chapters present the key findings and opportunities for future work in this area. The collective findings of the entire life cycle are addressed in Chapter 8: Discussion of MFA results. Lastly, the conclusions and recommended future work are presented in Chapter 9: Future work.

CHAPTER 2 METHODOLOGY

2.1 Introduction

This chapter first describes the methodology of Material Flow Analysis (MFA) in terms of its applications, strengths and weaknesses. Next, a literature review of relevant MFAs is presented. Five basic steps are taken to conduct a MFA—(i) defining the system boundaries, (ii) collecting data, (iii) assimilating into useful forms, (iv) accounting and (v) presentation of results. The first two steps are summarized in this chapter, while the other three steps are summarized for each of the five life cycle stages in the subsequent chapters.

2.2 Material Flow Analysis

A Material Flow Analysis (MFA) looks at the flows, accumulations and depletions of the stock and associated environmental impacts of a material within a specified region and time period (Wernick, 1998). Mass balances are performed for each set of system boundaries, i.e. total inputs must equal the total outputs and accumulation or depletion of stock by mass. The roots of MFA come from Quesnay's simple economic "tableau" model of the physical commodities flows of the French economy in the 18th century. It has since evolved past input-output economics and in 1980s and became popularized as the current form of tracing materials through physical process in the United States in the 1980s (Kneese et al, 1972 cited in de Haes et al, 1998). Typically, MFAs are used for the objectives described in Table 2.1.

Table 2.1 Objectives and examples of Material Flow Analysis

Objectives	Examples
Physical assessment	• To show the scale of bulk materials flow to meet the basic infrastructure needs of modern societies (de Haes et al, 1998) • To foresee future resource depletions
Environmental impacts	• To analyze the environmental impact associated with the functioning of modern industrial economies (Wernick, 1998). • For early recognition of future environmental loadings (Brunner 2003). • To link emissions to sources and vice versa (Brunner, 2003). • To find a compromised set of processes, flows and stocks of goods, substance and energy to ensure a sustainable economy.
Identifying critical issues for further investigation	• To identify major problem flows from the environment to the society and vice versa and to assess the degree to which material cycles are closed analytically and comparatively. (de Haes et al, 1998) • To identify opportunities for reducing impacts of the production and consumption processes, e.g. in the design of regional systems for creating loop-closing (Ehrenfed et al, 2002).

MFAs can be seen as an evolved version of LCAs (Life Cycle Analysis). The LCA is another industrial ecology methodology which is oriented to tracking the environmental impacts instead of the mass flows associated with a process or the life cycle of a product. A careful depiction of system boundaries is required in both types of studies, since the results can vary greatly with a slight change in the system boundaries. However, one reason why the MFA is preferred for the purposes of the study is due to the mass balance constraint embedded. In other words, physical feasibility limits are used in MFAs to verify the feasibility of the quantities of flows entering and leaving the system boundaries and to motivate the search for more remote and obscure flows (de Haes et al, 1998, Wernick, 1998.) The second reason is that the LCAs do not provide a good representation of materials use in the economy since they are normalized to a functional unit (e.g. 1 kg of concrete.) Hence, there are severe limitations in accounting for the diversity of concrete types[9] of varying raw materials composition used in the United States and for the different types of production and construction processes used.

In addition, with the use of simple matrices, MFAs are highly effective in showing the relationships between materials use and social dynamics (e.g. the efficiency of raw materials conversion) (Wernick, 1998.) Nevertheless, the documentation of environmental impacts is incorporated into the MFA to establish linkages between related materials use and environmental loads. However, these environmental impacts are only intended for gauging the linkages and are not normalized to global warming potential, acidification potential, etc. as is typically done in LCAs.

The main strengths and weakness of MFAs are presented briefly in Table 2.2. The MFA helps to minimize "quick-fix" short-term policies and is therefore an attractive decision-making tool for policy makers, resource managers and environmental agencies (Lowe, 1997). Furthermore, they could aid in setting priorities for management measures and the designing of new processes, goods and systems in view of environmental constraints (Brunner, 2003). The main disadvantage of MFAs is the difficulty in comparing different MFAs. In addition, using a static instead of a dynamic MFA model for this study does not allow for the development of scenarios for improving the performance of the system or the tracking of how future loads of the material studied might develop.

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[9] Examples: ready-mixed concrete, concrete masonry units and precast concrete. Ready-mixed concrete and concrete products are made using different production and construction methods.

Table 2.2 Strengths and weaknesses of Material Flow Analysis

Strengths
• *Serves as an error check* This is a crucial advantage over LCAs (Life Cycle Analysis)[10]. MFA uses physical feasibility processes as limits to account for inconsistencies in aggregation and identification of missing/unspecified flows (de Haes et al, 1998). Though the basis is partially theoretical, a balanced process can increase accuracy of empirical data by reducing error-bounds (Ayres and Ayres, 1998).
• *Increases transparency of accounts* MFAs provide an integrated view of the interactions between materials, energy and the environment by increasing transparency. Apparent and hidden movements of bulk materials in an economy are identified, catalogued and calculated (Wernick, 1998).
• *Useful for trend analysis of additions of stock and accessing sustainability* As derived from mass balances. Accessing sustainability within a specific unit of the economy is possible with available metrics, such as the efficiency of raw materials extraction (Lowe, 1997, Wernick and Ausubel, 1995 cited in Wernick, 1998.)
• *Extends the temporal and spatial impacts of societal and industrial activities to the actors.* MFAs have unveiled misconceptions through findings that show consumers, not producers, are the dominant polluters. (Wernick, 1998)
Weaknesses
• *Only for analytical, not comparative purposes* MFAs of different materials cannot be compared due to the descriptive non-normalized nature. There is also a lack of standardization of methodology, data verification and analytic methods (Wernick 1998).
• *This specific MFA is static, not dynamic.* For an even better representation, a dynamic model is preferred to factor in time as a variable to calculate the long term equilibrium and the conditions to achieve it (de Haes 1998). However, a large data set spanning several years or more has to be collected.
• *Due to the focus on an individual substance, the environmental impacts of substitution by another substance are left out.* On the other hand, MFAs could be supplemented by LCA studies, otherwise known as Material-Product-Chain (MPC) analysis (de Haes et al, 1998; Kandelaars et al, 1996).
• *Only measures throughput.* A major implication is the subconscious push for material efficiency not effectiveness, which deals more with supply-side management.

2.3 Literature review

When the built environment was first studied by urban planners and input-output economist, buildings were viewed as capital and physical stocks of the economy (Kytzia, 2004). Over time, buildings have come to be seen as stocks of construction materials in

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[10] In LCAs, energy and emissions to air and water are given in different units (e.g. MJ and mass units). This allows for biased assumption on things such as energy efficiency to project nearly zero emissions (Ayres and Ayres, 1998).

the context of environmental research, particularly in MFAs. The lifecycle spans from the resource extraction, production of building components, construction, maintenance and waste management. Past MFA applications in the built environment have focused on resource consumption, energy consumption and waste management (Kytzia, 2004, Kohler, et al 1997, Johnstone, 2001). Construction or building-related MFAs are relatively new compared to their rigorously and comprehensive MFA analyses for metals, heavy metals and other materials (zinc – Spatari et al, 2003, copper – Spatari et al, 2002, paper – Leah et al, 1997). Though most building materials are chemically-inert, they impose tremendous burdens on resources, cost, space and the environment due to the sheer mass of materials moved through the production, use, maintenance and disposal of buildings and other infrastructure. Therefore, a steady increase in building materials studies is foreseeable in the future.

MFAs are typically used to track the life cycle of construction minerals or the waste management life cycle stage of building materials. On the other hand, LCAs and Life Cycle Inventories (LCIs or the database of LCAs) are used to track environmental loads from the production of building materials and products (e.g. cement, masonry units and steel.) The key strength of the current study is the integration of material, water and energy flows and emissions produced for the lifecycle of concrete, which incorporates the strengths of both MFAs and LCAs. The most relevant MFA to this research is the study of waste concrete in the United States performed by Kelly/USGS (1998). However, its emphasis is on recycling waste concrete rather than tracking concrete through its entire life cycle. In addition, there are several LCAs on the life cycles of cement and of concrete. LCAs of cement tend to end at the 'gate' or the cement manufacturing plant, while LCAs of concrete focus specific concrete types (e.g. ready-mixed concrete and concrete masonry units) which does not account for the diversity of concrete types used in the United States and the different construction and production processes used. In other words, they do not give any indication of how concrete is used in the economy—e.g. the composition of concrete types and the dominant end-uses of concrete (e.g. buildings, highways and roads.) In essence, MFAs are much more effective in presenting the big picture of the mass flows of concrete produced and used in the United States, while LCAs provide a more accurate picture of the environmental impacts in terms of toxicity.

Works that are relevant to this thesis as well as a brief synopsis are presented in the following table:

Table 2.3 Summary of selected literature review on life cycle of concrete (by stage)

	Author	**Remarks**
'Extraction of raw materials'		
Construction minerals	McEvoy et al (2004)	For U.K. From extraction to waste management stages.
'Manufacturing of cement'		
Life cycle analysis (LCI) (includes material, energy and water, solid and liquid waste and emissions)	Buzzi Unicem (2004)	For an Italian cement plant. Certified by ICMQ S.
	AIA Environmental Resource Guide (1996)	Provides a comprehensive schematic of the life cycle of cement and concrete masonry units. Good representation of extraction of raw materials.
Life cycle inventory (LCA) (includes material, energy and water, solid and liquid waste and emissions)	Portland Cement Association (2002)	For Portland concrete and Portland cement.
	BEES (2002)	For concrete products.
	ATHENA (1999)	For Canada – cement and concrete products.
	Vares & Häkkinen (1998)	For Finland - concrete and concrete products.
	Vold & Rønning (1995)	For Nordic countries – cement and concrete.
'Production of concrete'/ 'Use of concrete'		
Trends in concrete use	Fernandez (2004)	For construction materials from 1970 – 2050.
Environment impacts of concrete design and on-site use	Brocklesby & Davison (2000)	For U.K – energy and CO_2 emissions by type of concrete mix.
Energy and greenhouse gas emissions during construction	Cole (1999)	For Canada - energy and CO_2 emissions from construction of different concrete structural systems.
'Waste management of concrete'		
Demolition survey	ATHENA (2004)	For Minnesota from 2000 - 2003. Shows composition and age distribution of building stock and reasons for demolition.
Waste concrete as composition of building-related construction &demolition (C&D) waste	Sandler (2003)	Gives further analysis based on Franklin/ EPA (1998) report.
Waste concrete	Kelly/USGS (1998)	Gives a good overview of material flows along life cycle of concrete.
Characterization of building-related C&D waste	Franklin/EPA (1998)	Most comprehensive national scale study on C&D waste conducted.

- All for the United States, unless otherwise stated.

2.4 Defining the system

To create a MFA, the general system boundary is first defined. For the current study, five life cycle stages of concrete are defined—(1) extraction of raw materials, (2) manufacturing of cement, (3) off-site production of concrete, (4) use of concrete and (5) waste management of concrete. Next, internal boundaries are created within each stage to minimize double counting and add conceptual clarity to the purpose and execution of the analysis (Wernick, 1998).

The key contribution of this thesis is to account for the diversity of concrete types and end-use categories through stages (3) – (5). This is done by (i) making a distinction between off-site and on-site production of concrete is made; and (ii) identifying and representing the dominant concrete types used in the United States and the corresponding production and construction types in the MFA. Moreover, an attempt to quantify the associated mass, water, energy and environmental flows of the stage (5) is made, despite the lack of available data.

In this study, mass balances of materials, associated solid waste, hidden flows, water and energy are applied to determine unspecified flows and accumulation or depletion of stock. Emissions, however, are the only exception. To better represent the sequence of flows, the results are presented diagrammatically. It should be noted that these life cycle stages may overlap in reality. Furthermore, the actual mass flows are time-dependent by some degree due to the seasonality of the construction industry. Percentages of flows are used for descriptive purposes instead of the more analytical metrics available such as 'intensity of use' and 'industrial conversion efficiency' (Wernick and Ausbel, 1995 cited in Wernick, 1998). The system boundaries and process flow charts for this MFA are defined in Table 2.4.

Table 2.4 Definitions of the cement/concrete Material Flow Analysis

Definitions	
Scope	Cradle (extraction of raw materials phase) to cradle (recycling in the post-use phase) Cement = Hydraulic cement (Portland cement & masonry cement)
Boundary layer	The anthroposphere covering all 50 states of United States with a total land area of 9.2 million square kilometers The majority of the raw material extraction (particularly limestone), cement and concrete production occur within the United States.
Processes	Five main processes: • Extraction of raw materials • Manufacturing of cement • (Off-site) production of concrete • Use of concrete • Waste management of concrete
Flows	Raw materials (including water), products (cement and concrete), waste (waste concrete and hidden flows), water and energy
Stocks	Stock of physical infrastructure: buildings, highways and roads and other infrastructure
Base year	1996: year with the most comprehensive data available and is pretty representative of the consecutive years
Basis	1 year since most statistics are reported on a yearly basis
Accuracy	To capture at least 80% of concrete total estimated flows using consistent, well-validated data for greater accuracy To focus on several dominant uses to gain greater accuracy

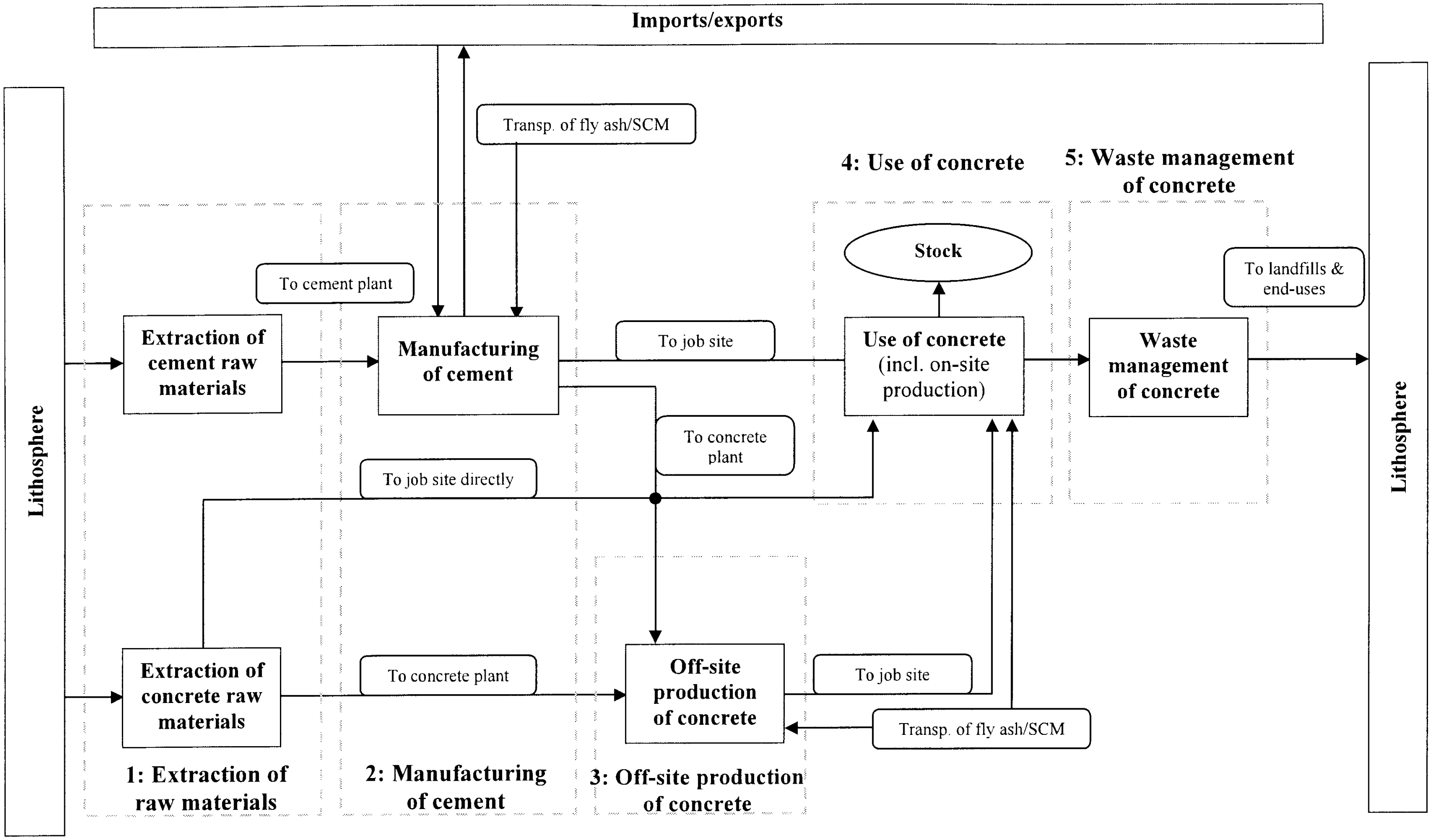

Figure 2.1 Process flowchart of current study

2.5 Collecting data

To account for the four types of flows (material, water, energy and fuel) and emissions produced, a comprehensive database is established. Firstly, the various data sources are listed. Next, the efforts in dealing with the data uncertainties are discussed.

2.5.1 Data sources

Though taking actual field measurements are preferred; they are not feasible due to the large scope of the present study. The difficulty of data collection increases as one moves further along the life cycle. The main sources of data are:

Table 2.5 Data sources by life cycle stage of concrete

Stage	Data sources
1. Extraction of raw materials	McEvoy et al 2004 AIA ERG 1996 USGS MYB and MCS 1996
2. Manufacturing of cement	BEES 2002 PCA LCI of Portland cement 2002 EIA 2000 ATHENA 1999 USGS MYB and MCS 1996 Vold and Rønning 1995
3. (Offsite) production of concrete	BEES 2002 PCA LCI of Portland cement 2002 ATHENA 1999 Kelly/USGS 1998 PCA Apparent use summary of cement 1998, 1999 USGS MYB and MCS 1996
4. Use of concrete	PCA LCI of Portland concrete 2002 PCA Apparent use summary of cement 1998, 1999 USGS MYB and MCS 1996
5. Waste management of concrete	Sandler 2003 EPA 2003 Franklin/EPA 1998 Wilburn & Goonan/USGS 1998

Five sources are pivotal in determining the environmental loads from raw materials extraction to production of concrete (see Table 2.6.) To estimate the allocation of cement among end-use categories and concrete types, two main sources are used: the 1998 PCA Apparent Use Summary and 1996 USGS Cement Mineral Year Book (MYB) and Mineral Commodities Summaries (MCS). On the other hand, waste management data comes mainly from the "Characterization of Building-related Construction and Demolition Debris in the United States" report for which selected projects from 10 states are surveyed (Franklin/EPA, 1998). However, this is specific only for one year and has no similar data from previous years to check the validity of the data.

Table 2.6 Main sources for environmental loads from cement and concrete production

PCA LCI Portland cement (2002)	78 kilns (43% of 180 operational kilns or 74% of total U.S. annual cement production of 85 mill metric tons).
	LCI results for an average metric ton of cement, not to any specific type.
	Apply to cement ground from domestically produced clinker, not cement ground from imported clinker, imported product.
	Data on energy input from 1999 PCA U.S. and Canadian Labor-Energy Input Survey (published in 2001).
PCA LCI Portland concrete (2002)	Energy used in concrete plants are from Forintek reports with the assumption that the concrete plants in Canada are similar to U.S. operations.
BEES (2002)	Based on PCA LCA database.
ATHENA (1999)	For Canadian cement plants in four regions.
Buzzi Unicem (2004)*	2003 Italian data.
	First cement plant in Italy to obtain ISO 14001 standard certification. Certified by the Swedish Environmental Management Council and ICMQ S.p.A..

** Data from Buzzi Unicem usually used as a check. If only one estimate is available, Buzzi Unicem is used as a proxy.*

2.5.2 Dealing with Data Uncertainty

Data uncertainties arise from various reasons:

- Differences in methodology and statistical integrity of data collection
- Changes in official statistics due to changes in industrial practice and conventions (Wernick, 1998). An example is the introduction of fly ash as a raw material in cement manufacturing in the USGS MYB
- Unclear definition of system boundaries
- Non-representative analytical methods with regard to the level of technology used and the geographical setting of the production plant
- Assumptions made due to lack of available data

To deal with such uncertainties, this thesis has tried to be as consistent as possible through various means:

- U.S. data sets are used as much as possible. If there is missing data or for checking purposes, data from other countries are used as a proxy.
- Multiple sources of data are used if available to compute best estimates, contrary to using single, most comprehensive sources which would provide greater consistency (Wernick, 1998). However, this is justifiable due to the lack of a database for the entire life cycle of concrete. Nevertheless, a single source is mainly used for computing emissions released.
- Where data is not available for 1996, data from within ± 3 years is used.
- To explicitly mention the possible differences due to various estimation procedures used to construct the account.

- A general 'rule of thumb' is to ensure that at least 80% of flows are captured as accurately as possible and to narrow down a few dominant uses (Spatari et al 2002).
- SETAC guidelines: inputs do not need to be included if (i) they are less than 1% of total mass of processed materials or product; (ii) they do not contribute significantly to a toxic emission, and (iii) they do not have a significant associated energy consumption.[11]

As a side note, this study does not included upstream production processes of fuel, machinery and facilities used. In addition, only quantifiable environmental impacts are accounted for.

2.6 Conclusions

This chapter has presented the methodology which will be used in this thesis, as well as a review of previous studies in this field and the main sources for the current study. It is demonstrated that the MFA is an ideal methodology for the purposes of this study due to two main reasons: (i) the embedded mass balance acts as a physical feasibility check for the quantities of flows entering and leaving the system boundaries and to motivate the search for more remote and obscure flows; and (ii) it is capable of accounting for the diversity of concrete products, end-use categories and production and construction techniques used in the United States and thereby provides a more representative picture of the concrete flows than the LCA. Through the literature review, it is shown that this work is original because no MFA has ever been conducted for the entire life cycle of concrete flows in the United States. The summary of the first two steps taken to conduct the current study is also presented via a list of data sources used and of the various measures which are used here to deal with data uncertainty.

In the next five chapters, the overview, results and linkages of material use and resource use, supply and demand dynamics and waste production are presented, namely

Chapter 3	Extraction of raw materials
Chapter 4	Manufacturing of cement
Chapter 5	Off-site production of concrete
Chapter 6	Use of concrete
Chapter 7	Waste management of concrete

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[11] Kotaji et al. 1993. Society of Environmental Toxicology and Chemistry cited in PCA, LCI of Portland Concrete; "Guidelines for Life-Cycle Assessment: A Code of Practice".

CHAPTER 3 EXTRACTION OF RAW MATERIALS

3.1 Introduction

This chapter and the subsequent four chapters will present the associated material, energy, energy and fuel flows and emissions produced for each life cycle stage of concrete in the United States in 1996. The first section provides relevant background information. The second presents the results in the form of a tabular summary and a diagram, followed by the details. Finally, preliminary conclusions of each stage are summarized in the last section.

3.2 Extraction of raw materials

Various raw materials are extracted for both cement manufacturing and concrete production. The most common raw materials for cement manufacturing are limestone, chalk and clay; although more than 30 raw materials are used to provide the calcareous, aluminous, ferrous and siliceous elements (Worrell et al, 2001; Greer et al, 1992 cited in Martin et al, 1999). Aggregates such as sand, gravel and crushed stones are mined for concrete production.

In 1996, approximately **124.8 Mt (million metric tons) nonfuel raw materials were used** to produce 79.2 Mt of cement (see Table 3.1.) This is equivalent to **1.6 t raw materials/t cement** or **1.8 t/t clinker**. The total raw materials required were closer to 1.62 t raw materials/t of cement or 128.7 Mt when other raw materials such as imported clinker and waste products (e.g. blast furnace slag and fly ash) are included (USGS Cement MYB 1996).

Table 3.1 Raw materials extracted for cement manufacturing in the United States in 1996

Raw materials	**Quantity (Mt)**	**%**
Calcareous:		
Limestone (includes aragonite, marble, chalk)	80.0	64.1
Cement rock (includes marl)	25.7	20.6
Coral	0.7	0.6
Aluminous:		
Clay	4.7	3.8
Shale	4.2	3.4
Other (includes staurolite, bauxite, aluminum dross, alumina, volcanic material, other)	1.1	0.9
Siliceous:		
Sand and calcium silicate	2.2	1.8
Sandstone, quartzite, other	0.6	0.5
Ferrous:		
Iron ore, pyrites, millscale, other	1.5	1.0
Other:		
Gypsum and anhydrite	4.1	3.3
Total	**124.8**	**100.0**

- Modified from USGS Cement MYB 1996
- Includes Puerto Rico. Assumed negligible since Puerto Rico uses only 2% of the raw materials.

In addition, the author estimates that **approximately 603 Mt aggregates** were mined for concrete production based on the current study results (see Table 3.2.) The quantity of natural aggregates extracted is within 3% of the estimate given by Wilburn et al (based on national statistics). Using PCA LCI of Portland Concrete concrete mix coefficients for the various concrete types, it is computed that 703 Mt aggregates was required for concrete production. This is 60% greater than the estimate of Kelly due to differences in the degree of aggregation of concrete types. In the current study, 12 concrete mixes (including mortar, concrete brick/block and 70 MPa precast concrete) are examined as opposed to one standard mix.

Table 3.2 Raw materials used for concrete production in the United States in 1996

	Mass (Mt)		
	Kelly/USGS 1998	**Wilburn & Goonan/ USGS 1998**	**Current study**
Sand & gravel	411	387	398[a]
Crushed stone	83.2	200	205[a]
Subtotal of natural aggregates	**494.2**	**587**	**603**
Waste concrete recycled into new cement concrete	5.7	n/a	100[b]
Total aggregates required	**500.0**	**>587**	**703[c]**

All figures are for 1996.

[a]: In this analysis, aggregates are either grouped as fine aggregates or coarse aggregates. To find the proportions of sand, gravel and crushed stone, the percentages of sand & gravel and crushed stone Wilburn et al (since it is based on national statistics) are used, e.g. sand & gravel 66%; crushed stone 34%. (Kelly's estimate is based on design mix.)

[b]: From off-site and on-site production of concrete and waste management of concrete in the post-use stage. This number is possibly slightly larger because a small quantity recycled from the use phase (construction, renovation/repair and demolition stages) has not been included due to lack of data.

[c]: As calculated using from PCA LCI of Portland concrete mix coefficients by concrete type.

- Wilburn and Goonan 1998: recycled uses include asphaltic concrete, road base and general fill but not new cement concrete.

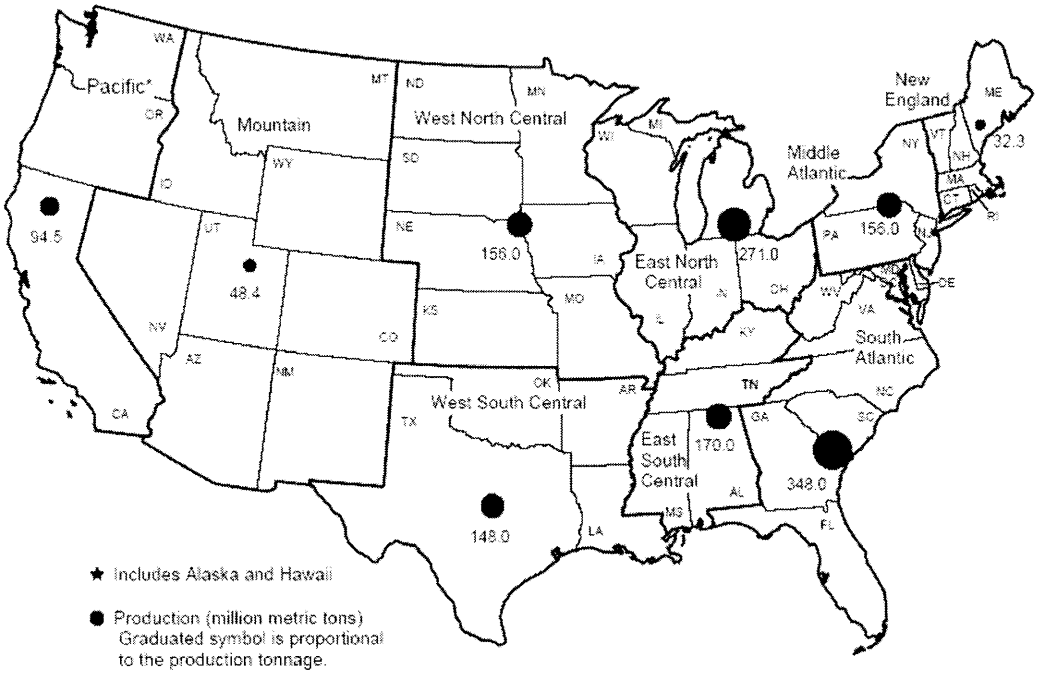
Most of the raw materials are mined from open-pits, scattered throughout the United States (Table 3.3 and Figure 3.1.) Variants of quarrying, mining and processing techniques are used for each type of raw materials are listed in Table 3.4. Electricity and diesel fuels are used to power heavy equipment for the mining and crushing processes (such as raw mills, primary and secondary crushing equipment, motors for blending, conveyor belts and dust collection).

Table 3.3 Geographical locations of lead producers by type of raw materials mined

Raw material	**Lead producers**
Limestone (& cement rock)	Pennsylvania, Illinois, Florida and Ohio
Clay & shale	Georgia, South Carolina, Florida and Arkansas
Iron ore	Minnesota, Michigan, Missouri, Pennsylvania, California and Wyoming
Gypsum	Iowa, Oklahoma, Michigan, Texa, Nevada, California and Indiana
Sand	California, Texas, Michigan, Ohio, Washington, Arizona, Illinois
Crushed stone (construction)	Texas, Pennsylvania, Missouri, Florida, Georgia, Illinois, Ohio

(References: Clifton et al, 1977 cited in Renfoe, 1979, AIA ERG, 1996, USGS MCS, 1996)

Figure 3.1 Production of crushed stone in the United States in 1997, by geographic division



(Source: Tepordei/USGS, 1997 - *Includes limestone, sandstone and quartzite)*

Table 3.4 Mining techniques and energy uses by type of raw materials mined

	Mining technique	**Processing technique**
Limestone (cement rock & crushed stone)	Open-pit mining or quarrying: blasted from surface mines with explosives; overburden removed using bulldozers, draglines or hydraulic shovels; broken rock transported away in large dump trucks. Tailings waste left at mine site.	Crushed or ground. Calcined in kilns to produce quick lime.
Clay & shale	Surface/open-pit mining: overburden soil removed using scrapers or draglines; clay mined using shovels, draglines, scrapers or front-end loaders; loaded in trucks or made into slurry to be pumped to degritting station.	Crushed; coarse grit removed from clay using settling boxes, screens and hydrocylones; next pumped to beneficiation plant; blending.
Iron ore	Surface/open-pit mining: ore and waste rock dug out using power shovels, rotary drillls and trucks.	Most are beneficiated (crushed, screened, dried, washed and ore minerals separated from gangue.) May also be sintered (thermally fused) or palletized using binders.
Gypsum	Quarrying or open-pit mining: overburden removed using draglines and scrapers; gypsum drilled and blasted with rotary or auger drilling.	Crushed, screened and ground; calcined in kilns.
Sand	Open-pit excavation and dredging mining. Extracted from surface deposits after removing overburden soil	Crushed, screened and ground; washed and graded to remove chlorides from marine-derived materials or excessive amounts of clay and silt from land-based sources.

(Reference: AIA ERG, 1996)

After the raw materials are mined and processed, they are trucked to the crushing equipment of the cement plant, which is usually adjacent to the quarry within 16 km radius. If the cement plant is further away, the raw materials are transported by barge on inland waterways (Klemm 1995 cited in AIA ERG, 1996).

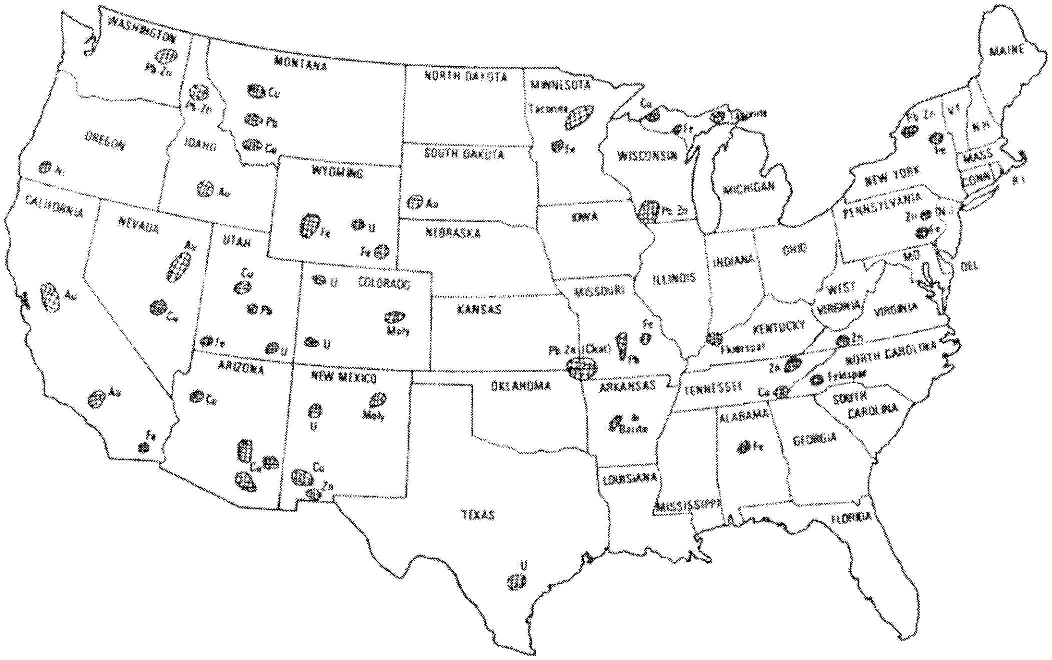
Due to the nature and large scale of raw materials extraction, environmental impacts are evident. Firstly, quarrying and mining produce two main types of waste: waste rock and overburden, and mill tailings (or waste that is separated from valuable ores after processing.) The removal process of waste rock and overburden poses environmental problems though the materials are not toxic. They are typically disposed of in large dumps or used as backfill in open-pit mining operations and in highway construction. On the other hand, tailings are a concern because of water pollution and are disposed of in tailing ponds as iron slimes or as backfill materials in mines. A map of waste rock and mill tailing accumulations is shown in Figure 3.2. In addition, some of the other environmental impacts of raw materials extraction are summarized in Table 3.5. On the other hand, alternatives to quarrying and mining do exist. In the case of limestone mining, alternatives include a switch to producing magnesium cement, replacement with oil palm shells and changing or minimizing admixtures used in cement manufacturing.

Table 3.5 Environmental impacts of 'Extraction of raw materials' stage

		Environmental impacts
Disturbs	Land	Landscape disturbance, loss of agricultural land, soil contamination
	Ecosystems	Flora and fauna damage; possible fishkill
	Humans	Health impacts, noise
Pollutes	Water	Runoff from tailings waste causes surface water and groundwater contamination; deoxygenation of aquatic habitats by increasing biological oxygen demand (BOD); increased sediment loads
	Air	Fugitive emissions of greenhouse gases and VOC, SO_2, NO_x, CO, dust which cause ozone/smog, acid rain, respiratory tract, cardiovascular and nervous system problems

(References: Ripl, 1994 cited in von Weizsäcker, 1998, AIA ERG, 1996, van Oss, USGS, 1996)

Figure 3.2 Accumulation of waste rock and mill tailings, by geographic division (Clifton et al, 1977 cited in Renfoe, 1979)



3.3 MFA results

3.3.1 System boundaries

The processes included in the system boundaries are:

(i) **Quarrying/mining** of raw materials for
  - cement manufacturing (limestone, clay and shale, etc.)
  - concrete production (sand, gravel and crushed stone).

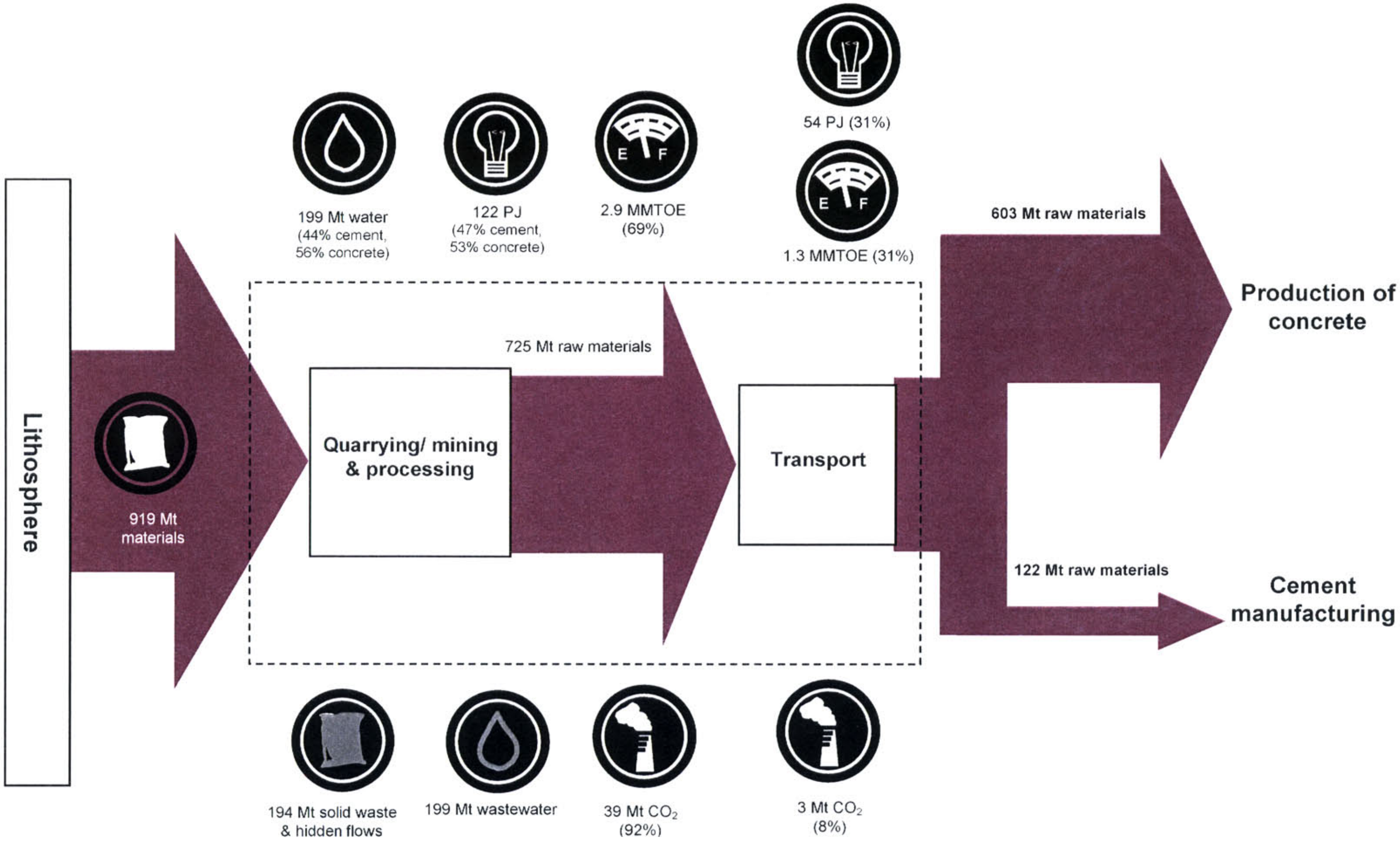
  Includes blasting, drilling, digging and loading.

(ii) **Processing** of raw materials.

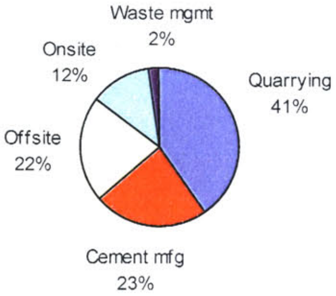
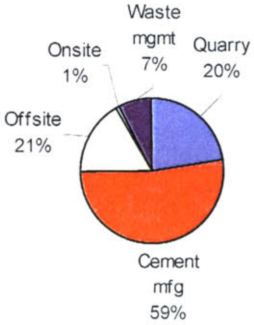
  Includes crushing, screening and washing.

(iii) **Transportation** of
  - cement raw materials to cement manufacturing plant (including conveying and stockpiling)
  - concrete raw materials to
    - ready-mix concrete plant or concrete product plant for off-site batching/prefabrication
    - job site directly for on-site batching and use.

3.3.2 MFA of 'Extraction of raw materials'



3.3.3 Summary

<table>
<tr><th></th><th>Input</th><th>Output</th></tr>
<tr><td>Materials</td><td>919 Mt materials moved
≡ 9,200 Empire state buildings
<i>[Total materials (including water) throughput = 1,120 Mt]</i></td><td>725 Mt raw materials
≡ 7,250 Empire state buildings +
980 Mt hidden flows</td></tr>
<tr><td>Water</td><td>199 Mt water ≡ annual water consumption of 3 mill people
(population of Chicago, Ill. today)
 </td><td>199 Mt effluent</td></tr>
<tr><td>Energy</td><td colspan="2">176 PJ or 0.24 GJ/t raw material
≡ annual energy consumption of 433,000 people
Processing = 122 PJ (69%), Transportation = 54 PJ (31%)

Piechart is similar for fuel and CO_2 emissions.</td></tr>
<tr><td>Fuel</td><td colspan="2">4.2 MMTOE ≡ annual fuel consumption of 3 million automobiles</td></tr>
<tr><td>Emissions</td><td>-</td><td>42 Mt CO_2 ≡ annual CO_2 emissions of 0.9 mill automobiles</td></tr>
</table>

3.3.4 Details of MFA

(a) Materials

Consistent with the SETAC guidelines, the system boundary of this lifecycle stage covers the mining and quarrying of the raw materials which are greater than 1% of the total raw materials by mass, i.e. limestone, cement rock, clay, shale, sand and calcium silicate, iron ore, gypsum and anhydrite. Altogether, 95% of the total raw material flows is accounted for. The production of fly ash is not included in this stage because it is a coal combustion waste-product and does not require raw materials extraction. Instead, the transportation energy of fly ash (from coal power plants to cement plants) is included in the 'Manufacturing of cement' stage. In addition, cement rock is aggregated with limestone in this analysis since they use similar quarrying technology and fuel use composition and share the same NAICS number (212312). Furthermore, 'materials moved' refers to the raw materials extracted, hidden flows and solid waste.

From the current study, it is found that **the total materials moved amounts to 919 Mt for the extraction and processing of 725 Mt of usable cement raw materials (17%) and concrete raw materials (83%).** The **27% extra total materials (447 Mt) moved signifies the quantity of hidden flows** [12]incurred in the form of ore processing waste and overburden (22% for cement raw materials, 28% for concrete.) For the same year, '*The Weight of Nations*' indicates that approximately 2,500 Mt of mineral, mining overburden and waste was produced (World Resource Institute, 2000). By comparison, **extraction of cement and concrete raw materials accounts for 18% of the total minerals, mining overburden and waste produced in the United States in 1996**. The overburden and majority of wastes (waste rock) are produced during the extraction. Process waste from further treatment of the raw materials (e.g. crushing and washing) are deemed small and are typically dust released from fugitive and controlled point sources (PCA LCI of Portland cement, pg. 7). The only exception is the process waste of iron ores. It is estimated that 5.2 tons of waste rock and mill tailings are produced for every one ton of usable iron ore.[13] In addition, **the quantity of concrete raw materials moved is five times greater than cement raw materials** for a given volume of concrete. If recycled aggregates[14] are excluded, the ratio increases to 6:1.

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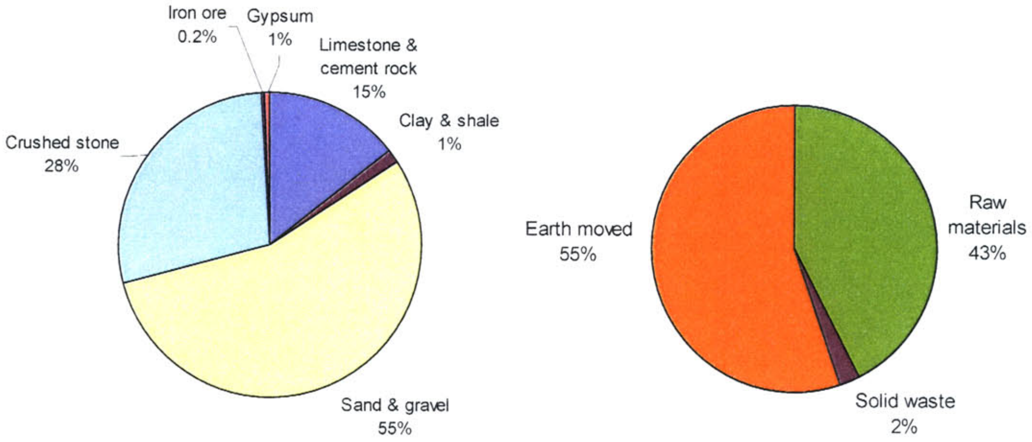
[12] Hidden flows are bulky and inert materials displaced due to materials consumption (e.g. waste rock, overburden and ore processing waste). They are typically of large scale and transported over short distances (Berkhout, 1998).

[13] USGS Mining MYB 1996 states 6.2 tons of waste is produced for 1 ton of usable iron ore.

[14] Refer to Chapters 5, 6 and 7.

Figure 3.3 Outputs of raw materials extraction for cement and concrete production



By type of raw materials **By type of output categories**

Table 3.6 Materials mass balance for raw materials extraction

	Total materials moved (Mt)	Raw materials for cement (Mt)	Raw materials for concrete (Mt)
Inputs			
Lithosphere materials	**919**	149	771
Water	**199**	105	94
Total inputs	**1,118**	**254**	**865**
Outputs			
Raw materials extracted			
- Limestone	**80**	80.0	-
- Cement rock	**26**	26	-
- Clay	**4.7**	4.7	-
- Shale	**4.2**	4.2	-
- Sand, calcium silicate & gravel	**~400**	2.2	~398
- Crushed stone	**~205**	-	~205
- Iron ore & other	**1.5**	1.5	-
- Gypsum & anhydrite	**4.1**	4.1	-
Total usable raw materials	**725**	122	~603
Total waste	**393**	132	262
- Solid waste & hidden flows/overburden	194	27	168
- Wastewater	199	105	94
Total outputs	**1,118**	**254**	**865**

Only materials in system boundary included.

(Sources: USGS Cement MYB 1996 for cement raw materials, MFA results for concrete raw materials)

[a]: Not including solid waste produced from sand and gravel extraction.

[b]: Not including earth moved during iron ore extraction

Table 3.7 Total solid outputs for 'Extraction of raw materials' stage

For cement (Mt)		For concrete (Mt)		Total	
Solid waste[*]	**Total earth moved**	**Solid waste[*]**	**Total earth moved**	**Solid waste[*]**	**Total earth moved**
27	149	168	771	919	194

For 122 Mt cement raw materials and 603 Mt concrete raw materials (398 Mt sand & gravel and 205 Mt crushed stone). Calculations based on USGS Mining & Quarrying MYB 1996, Douglas and Lawson (1997) cited in McEvoy et al (2004)) – see Table 3.8.

[*] Includes waste rock, mill tailings and overburden in some cases.

- Solid waste from raw materials transportation is assumed negligible since it is found to be 0.02% of raw materials transported based on Buzzi Unicem coefficients. (0.00027 t solid waste/ t cement for raw materials transportation.)

Table 3.8 Total materials moved coefficients for 'Extraction of raw materials' stage

References	**Moavenzadeh (1990); Barney[a] (1980)**	**Clifton et al, 1977 cited in Renfoe, 1979[b] (1977)**	**Moavenzadeh (1990); Barney (1980)**	**Renfoe[b] (1977)**	**USGS Mining MYB 1996**	**Moavenzadeh (1990); Barney[a] (1980)**	**Clifton et al, 1977 cited in Renfoe, 1979[b] (1977)**	**McEvoy et al (2004); Douglas & Lawson (1997)**	**Current study**
Year	**1976**	**1970s**	**1976**	**1970s**	**1996**	**1976**	**1970s**	**1990s**	**1996**
	Waste rock (t/t mineral)		**Mill tailings (t/t mineral)**		**Total solid waste (t/t mineral)**			**Earth moved multiplier**	**Total materials moved**
Limestone, cement rock, crushed stone	0.0779	n/a	0.0130	n/a	0.079	0.909	n/a	1.2	**1.08**
Clay & shale	0.806	n/a	-	n/a	0.87	>0.806	n/a	1.5	**1.87**
Sand and gravel	-	n/a[c]	-	n/a[c]	n/a	-	n/a	1.38	**1.38**
Iron ore	3.45	0.328	2.13	0.328	0.83[d]	5.58	0.656	n/a	**6.2[d]**
Gypsum	n/a	1.29	n/a	0.245	0.36	n/a	1.535	1.2	**1.36**

All ratios computed by author except for Douglas & Lawson's multipliers.

[a]: Includes overburden in some cases. For 'Mining' waste.

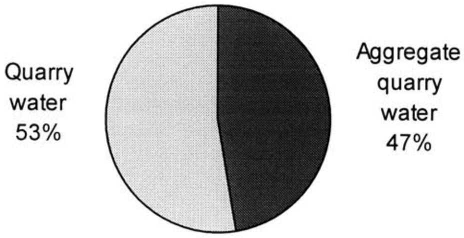
[b]: Converted to a ratio by author. Since it is not stated which year the data is for, the quantity of solid waste and millings per unit mass of minerals are calculated using the averages of USGS data on minerals production for the 3 preceding years (1974 – 1976; USGS).

[c]: Difficult to compute coefficient from the aggregated category of 'Quarry'.

[d]: A ratio of 0.825 t solid waste/ t crude iron ore is computed from USGS 1996 Mining MYB. In the same publication, another figure is quoted: 6.2 t total materials moved for 1 t usable ore, which is used for the multiplier of earth moved.

(b) Water

For the 603 Mt raw materials extracted and processed, **approximately 199 Mt water** was used for the processing stage (not including embodied water.) Aggregate quarry water (water used for quarrying/mining concrete raw materials) consists of 47% of the total, while quarry water makes up the remaining 44%. These values are calculated using per metric ton cement coefficients for quarry water and per metric ton aggregate coefficients for aggregate quarry water (see Table 3.10.) For the same mass, **cement raw materials require four times more water than concrete raw materials** in the extraction stage. A possible reason is the inclusion of water used for wet processing of separating tailings from iron ores and transporting the tailings as slurry for disposal. Embodied water is not included because of the high uncertainty in determining the moisture content of each type of raw materials, which could range from 1 to more than 50% (EPA AP-42 1994) and the changes in embodied water in the raw materials during processing, cement manufacturing and concrete production. If embodied water is included into the water use at arbitrary 8% initial moisture content, the total water consumption could increase by an additional 30%.



(For domestic production of 79.3 Mt cement and consumption of 603 Mt as concrete aggregates).

Figure 3.4 Water consumption of 'Extraction of raw materials' stage

Table 3.9 Total water used in extraction of raw materials

Water use & wastewater generation (Mt)		
Quarry water	**Aggregate quarry water**	**Total influent/effluent**
105	94	199

- For 90.4 Mt cement (or 122 Mt raw materials) and 603 Mt aggregates for concrete production.
- May not add up to total due to independent rounding.

Table 3.10 Water use coefficients of extraction of raw materials stage

	ATHENA & AIA	Buzzi Unicem	Current study
Inputs			
Cement: Quarry water (kg/t cement)	1,017	1,454	**1,157***
Concrete: Aggregate quarry water (kg/t aggregates)	*235*	n/a	**156***
Outputs			
Cement: Quarry wastewater (kg/t cement)	-	1,454.2	**1,157**
Concrete: Aggregate quarry wastewater (kg/t aggregates)	-	n/a	**156**

'Quarry water' specific for cement raw materials and 'Aggregate quarry water' for concrete raw materials.

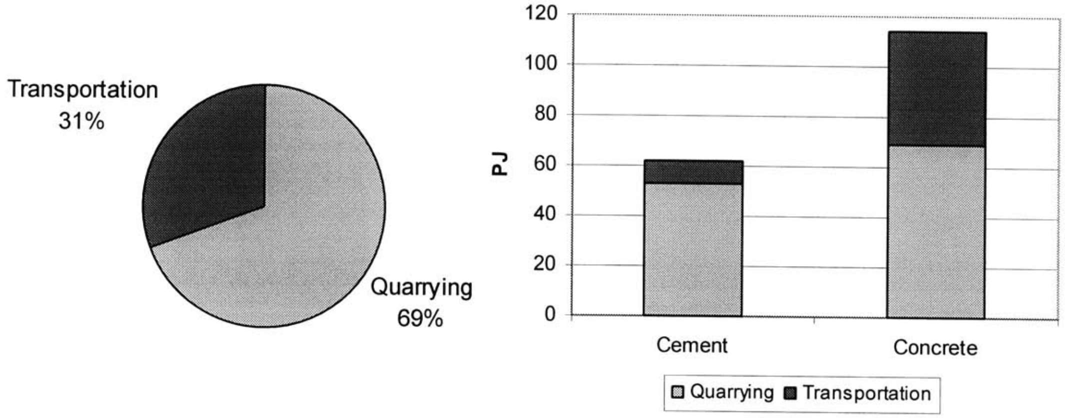
* Average of ATHENA and Buzzi Unicem after discounting for embodied water retained in the aggregates (78.9 kg water/ t aggregates; computed from AIA ERG 1996 – see below.)

- ATHENA: Author computes average of of 20 MPa and 30 MPa ready-mixed concrete.
- Buzzi Umicem: Sum of 1,444.19 L/t cement for resources production and 9.97 L/t cement for resources transportation.
- AIA ERG: author deduced 0.6 – 1.8 gall is retained in the aggregates as embodied water or 80.2 – 240.6 L water/m^3 concrete (since typical total water content for a concrete masonry block is given as 3.0 – 3.6 gall water/ ft^3 concrete, where 1.8 – 3.0 gall of additional water/ft^3 concrete is added to the existing water in the aggregates.) The average embodied water is 160.4 L water/m^3 concrete or 78.9 L water/ t aggregates (using coefficient of 2.033 t aggregates/ m^3 for a concrete masonry block). This is equivalent to 8% initial moisture content, which is within range of 1 to more than 50% given in EPA AP-42 (1994).
- PCA LCI of Portland concrete gives the water application rates when transporting aggregates from quarry as 0.846 L/m^2 at every 3-4 hour intervals. However, the quantity of water used for water application is assumed small.
- It is not noted if water input includes slurry water for tailings.

(c) Energy

The total amount of energy required is approximately **176 PJ (about 45% of cement manufacturing energy** – see Chapter 2: Manufacturing of cement.) Processing accounted for **122 PJ energy** used, while transportation accounted for **54 PJ**. Cement raw materials required 35% of the total energy (62 PJ), while concrete raw materials consumed the remaining 65% (114 PJ.) Several approaches, based on mass/volume of product or by mass of raw materials, are used to estimate the processing (quarrying and mining) energy and transportation energy required. Alternatively, the processing energy consumption could be estimated from U.S. Census Bureau 1997 reports, which breaks down the fuel use by type. However, other fuels such as liquefied petroleum gas, gas and coke and undistributed fuels are not quantified. In addition, there are undisclosed data gaps. For example, the monetary value and the quantity of coal used for iron ore mining are undisclosed.

In general, the raw materials can be grouped into two groups. Sand, gravel and gypsum have mining energy varying from 19 – 47 MJ/metric ton raw materials; while limestone, crushed stone, clay and shale have mining energy varying from 44 – 155 MJ/metric ton raw materials[15]. The energy requirement of the second group is typically double that of the first group.



By process **By raw materials type**

Figure 3.5 Energy use of 'Extraction of raw materials' stage

Table 3.11 Total energy use for 'Extraction of raw materials' stage

	Raw materials for cement		Raw materials for concrete	
	Quarrying (PJ)	**Transportation (PJ)**	**Quarrying (PJ)**	**Transportation (PJ)**
Estimates				
PCA, LCI of Portland cement	6.3[a]	1.3[a]	-	-
PCA, LCI of Portland concrete (by per ton raw material)	-	-	35.3[b]	32.0[d]
PCA, LCI of Portland concrete (by concrete product)	-	-	**43.8**[c]	**33.1**[c]
AIA ERG	**> 36.3**[d]	> 62.4[d]	-	-
ATHENA	3.5[a]	**6.3**[a]	-	-
BEES	-	-	**93.5**[e]	**56.9**[e]
Checks with data from other countries				
Italy/ Buzzi Unicem	**68.6**[a]	**11.9**[a]		
UK/ McEvoy et al	> 5.2	-	16.7[a]	-
Current study/average	**~53**[f]	**~9**[g]	**~69**	**~45**
Current study/total	**~62**		**~114**	

(For coefficients, see Appendix A.)
[a]: For 79.3 Mt cement produced domestically in 1996.

---

[15] The lower bound is more frequently quoted in the literature.

[b]: For 463 Mt sand & gravel and 240 Mt crushed stone (as estimated from current study and mass balances.)

[c]: For 386 mill m^3 of concrete.

[d]: For total of 122 Mt cement raw materials.

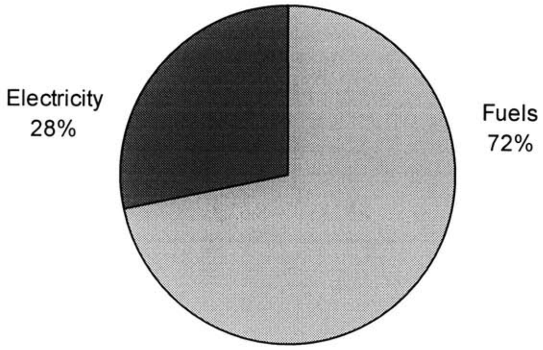
[e]: For 603 Mt of aggregates (total estimated from mass balances of this study.)

[f]: Energy used for extraction of concrete raw materials is determined with greater uncertainty. Since cement raw materials is 20% concrete raw materials by weight, the minimal amount of extraction energy (20% that of concrete raw materials) is about 19 PJ. Therefore, the answer is the average of estimates greater than 19 PJ (since cement raw materials extraction tends to be more energy-intensive due to iron ore extraction.)

[g]: Similarly, transportation energy is estimated to be about 20% that for concrete raw materials. This also happens to be the average of the ATHENA and Buzzi Unicem data.

(d) Fuel

The fuel consumed in extraction was **4.2 MMTOE**. Based on PCA LCI of Portland cement assumptions that a) approximately 56% of quarrying and mining energy is supplied by electricity and 44% by diesel fuel[16] and b) 100% of transportation energy by diesel fuel, the fuel mix for this stage is shown in Figure 3.6.



Fuels include gasoline and middle distillates/diesel fuels.

Figure 3.6 Fuel use of 'Extraction of raw materials' stage by fuel type

Notes:

- PCA LCI of Portland cement assumes 50% truck diesel, 50% rail diesel (though barge diesel is also used.)
- Vold & Rønning (1995) also gives similar fuel mix for quarrying/processing energy.

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[16] Percentage distribution of energy inputs for dry process kiln with preheater.

(e) Emissions

An estimated **42 Mt of CO_2** was produced from this stage, of which 41% is attributed to the extraction of cement raw materials and 59% to concrete raw materials. The processing stage produced approximately **39 Mt CO_2**, while the transportation stage produced an estimated **3 Mt CO_2**.

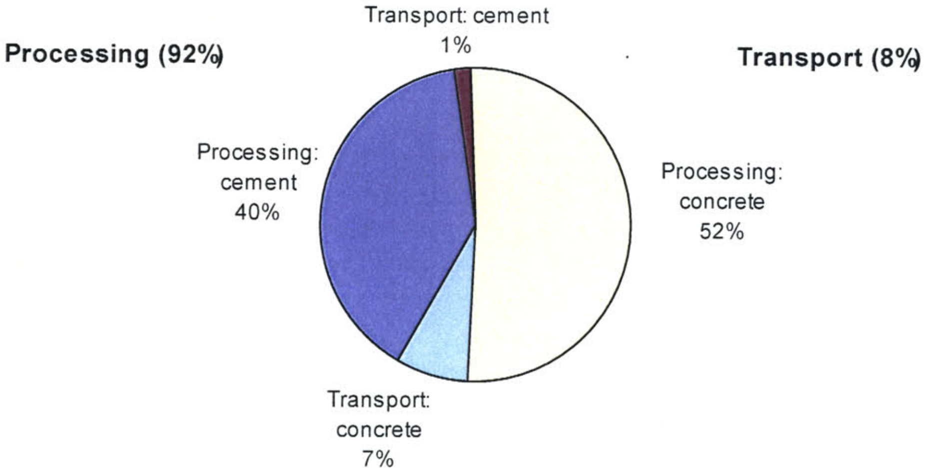


Figure 3.7 Total CO_2 emissions from 'Extraction of raw materials' stage

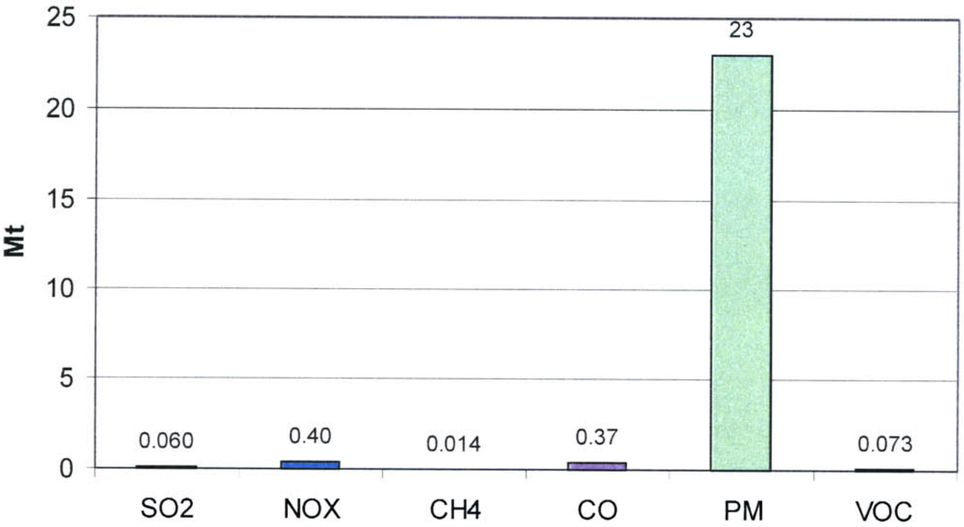


Figure 3.8 Total emissions from 'Extraction of raw materials' stage

Notes:

- For emissions by processing and transportation stages, see Appendix A: Table A 7.
- For emission coefficients, see Appendix A: Table A 8.

3.4 Preliminary conclusions

1. **For 1 metric ton of usable cement and concrete raw materials, 1.3 metric tons of materials have to be moved**. The additional 30% of materials are attributed to hidden flows, such as waste rock, overburden and ore processing waste.
2. In 1996, the extraction of cement and concrete raw materials accounted for **18% of the total minerals, mining overburden and waste produced** in the United States.
3. **The quantity of concrete raw materials moved is five times greater than cement raw materials** for a given volume of concrete. If recycled aggregates are excluded, the ratio increases to 6:1.
4. **The extraction and processing of cement raw materials require four times more water than concrete raw materials of the same mass**. This is probably due to water used for wet processing of separating tailings from iron ores used in cement manufacturing and transporting the tailings as slurry for disposal.
5. The processing and transportation energy used in the extraction stage can be as high as 45% of cement manufacturing energy (estimated at 176 PJ).

As mentioned earlier, this study includes quantifiable environmental impacts only. It should be noted that while most of the solid waste and overburden produced are relatively benign, the iron ore mill tailings, runoff, landscape disturbance, water and land contamination from tailings, etc do impose significant and intangible environmental burdens. Now that the raw material extraction has been accounted for, it is possible to consider the manufacturing of cement.

CHAPTER 4 MANUFACTURING OF CEMENT

4.1 Introduction

The United States is the third largest cement producer in the world, after China and India. In 1996, 79.3 Mt (million metric tons) of cement is produced, of which 50% is produced by California, Texas, Pennsylvania, Michigan, Missouri and Alabama (in decreasing order) (USGS Cement MCS 1996). The majority of cement produced is Portland cement (75.8 Mt or approximately 96% cement produced) while the remaining is made up of masonry cement (3.5 Mt). The number of cement plants (including Puerto Rico) has remained constant in recent years: 118 in 1996 to 116 in 2005. Accounting for imports, exports and additions to cement stock (from inventories at cement mills), the (net) apparent consumption in 1996 is 90.4 Mt. Canada, Spain and Venezuela are the top 3 countries which the United States gets its 11.6 Mt of imported cement (about 15% of domestic of production). Moreover, the majority of the 0.8 Mt exports (1.0% of domestic production) are exported to Canada. The various types of Portland cement produced domestically are given by the shipments of Portland cement (in the U.S. and Puerto Rico):

Table 4.1 Types of Portland cement shipped (USGS 1995 Cement MYB Table 15)

Type	Quantity (Mt)	%
General use and moderate heat (Type I and II) (Gray)	75	90.4
High early strength (Type III)	2.9	3.5
Sulfate resisting (Type V)	2.0	2.4
White	0.6	0.7
Blended*	0.83	1.0
Oil well	1.0	1.2
Block	0.4	0.5
Expansive and regulated fast setting	0.08	0.1
Miscellaneous	0.09	0.1
Total**	83	100

* *Blended cement includes Portland-slag, Portland pozzolan, blends with fly ash and silica fume.*
** *Does not include cement consumed at plant.*

In addition, the price of Portland cement is relatively high for a manufactured material (ranging from $70 to $93/metric ton in 1996). Subsequently, the cement manufacturing industry is considerably efficient in minimizing cement wastages and usage and in minimizing production costs, as this chapter will demonstrate.

4.2 Cement manufacturing

In essence, cement manufacturing is the chemical transformation of specific compositions of raw materials to di- and tri-calcium silicates and aluminates under highly-controlled conditions and extremely high temperatures. The main processes are (i) raw materials preparation, (ii) pyroprocessing and (iii) finish grinding process.[17]

(i) Raw materials preparation

Calcareous (Ca-containing), aluminous (Al-), siliceous (Si-) and ferrous (Fe-) raw materials (e.g. limestone, clay, sand and iron ore respectively) are first crushed using primary and secondary crushers (e.g. hammer mills or gyratory crushers) and homogenized (or weighed to specific proportions and blended together). When needed, the raw materials are further ground into raw meal of specified chemical composition and fineness in a ball or tube mill (using steel balls) or a vertical roller mill (against a rotating table) until at least 80% passes through a 200-mesh sieve. For use in wet-processing kilns (an older processing technique for easier mixing and proportioning), water is added to the raw meal to create slurry. However, the moisture needs to be removed, thus wet-processing kilns are more energy-intensive. Energy-efficient kilns include a preheater tower, which has vertical cyclone chambers heated to 20 – 900 °C by waste heat from the kiln.

(ii) Pyroprocessing

Next, the raw meal is fed downwards into a long rotary kiln, which is an approximately 6 m diameter tube. The kiln is inclined 3-4° horizontally and rotates at 1 - 4 times/minute. The majority of cement kilns in the United States are dry kilns (~75%), while the remainder are wet or semi-wet kilns. As the raw meal moves down the kiln towards the flame and gets heated up to 1,400 – 1,600°C, it undergoes four types of physical and chemical transformations:

I. **Drying & dehydrating** free/structural water in the raw meal

II. **Calcination**: raw meal decomposes thermally and loses bound water and carbon dioxide, i.e. calcium carbonate ($CaCO_3$) changes to calcium oxide (CaO) and carbon dioxide (CO_2).

$$CaCO_3 \rightarrow CaO + CO_2$$

III. **Clinkering/sintering:** Calcium oxide reacts with other oxides to form semi-fused dicalcium and tricalcium silicates (C_2S and C_3S) in the form of marble-sized clinker. Small amounts of trialuminum aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) are also formed, i.e.

$$29C + 8S + 2A + F \rightarrow 6C_3S + 2C_2S + C_3A + C_4AF$$

---

[17] References for this section: AIA ERG 1996 and van Oss USGS 1996 Cement MYB.

Table 4.2 Chemical formula for short notation used in equations

Chemical formula	Short notation
CaO	C
SiO_2	S
Al_2O_3	A
Fe_2O_3	F
Ca_2SiO_4	C_2S
Ca_3SiO_5	C_3S
$Ca_3Al_2O_6$	C_3A
$Ca_4Al_2Fe_2O_{10}$	C_4AF

IV. **Cooling** of clinker in a grate cooler, a tube/rotary cooler or a planetary cooler

Pyroprocessing is probably the most complex and highly-regulated process in the life-cycle of concrete. Different crystalline intermediate compounds are produced at different temperatures; therefore using the right flame type is crucial. In addition, due to the large quantities of fuel combusted (mainly coal in the United States) and the calcination process, cement manufacturing is a major industrial CO_2 emitter (3-8% in the world from World Resources Institute, 1995; World Business Council of Sustainable Development, 2002; ATHENA SMI, 1999 cited in Chaturvedi, 2004; Mehta, 1998). Besides CO_2, other pollution such as NO_x, SO_x, heavy metals and dioxins are produced from the fuel combustion. The recent trend of increased use of waste fuels (e.g. waste tires, spent fuels, rice husks, etc.) has also resulted in the increase of greenhouse gas emissions. Nevertheless, it has been argued that cement kiln combustion is a good way to dispose of waste tires and other waste products because toxic volatile organic compounds (VOCs) are destroyed under such high temperatures. To reduce the thermal energy required by the kilns, cement manufacturers have been installing precalciners to preheat the raw meal so that 80-95% of $CaCO_3$ is calcined or dissociated before moving into the kiln.

Another environmental concern is the cement kiln dusts (CKD), which are particulates of clinker, partially-reacted raw materials and solid fuels and materials eroded from the kiln's refractory brick lining. Almost all CKD is captured by either electrostatic precipitation or baghouse filtration for reuse as kiln feed, soil condition for farms, or sent to landfills. However, concerns remain about the high levels of hazardous trace-element or organic contaminants (such as chromium compounds from refractory bricks and nickel and vanadium from fossil fuels) (van Oss, USGS Cement MYB, 1996).

(iii) Finish grinding

Lastly, cement is ground with additives (e.g. gypsum, fly ash, blast furnace slag, pozzolan and anhydrite) in ball mills, roller mills or roller presses to stabilize the cement hydration and to control cement properties (e.g. setting time). The composition of Portland cement is shown in Table 4.3.

Table 4.3 Typical composition of Portland cement (van Oss & Padovani 2002)

Chemical formula	Short notation	Amount
Ca_3SiO_5	C_3S	50 – 55%
Ca_2SiO_4	C_2S	19 – 24%
$Ca_3Al_2O_6$	C_3A	6 – 10%
$Ca_4Al_2Fe_2O_{10}$	C_4AF	7 – 11%
$CaSO_4{\cdot}2H_2O$	$C\underline{S}H_2^*$	3 – 7%

*: Also known as calcium sulfate dehydrate (gypsum).

On the other hand, masonry cement is produced by from Portland cement or clinker directly and requires a high percentage of admixtures (typically ground limestone or lime).

4.3 MFA results

4.3.1 System boundaries

The processes included in the system boundaries are:

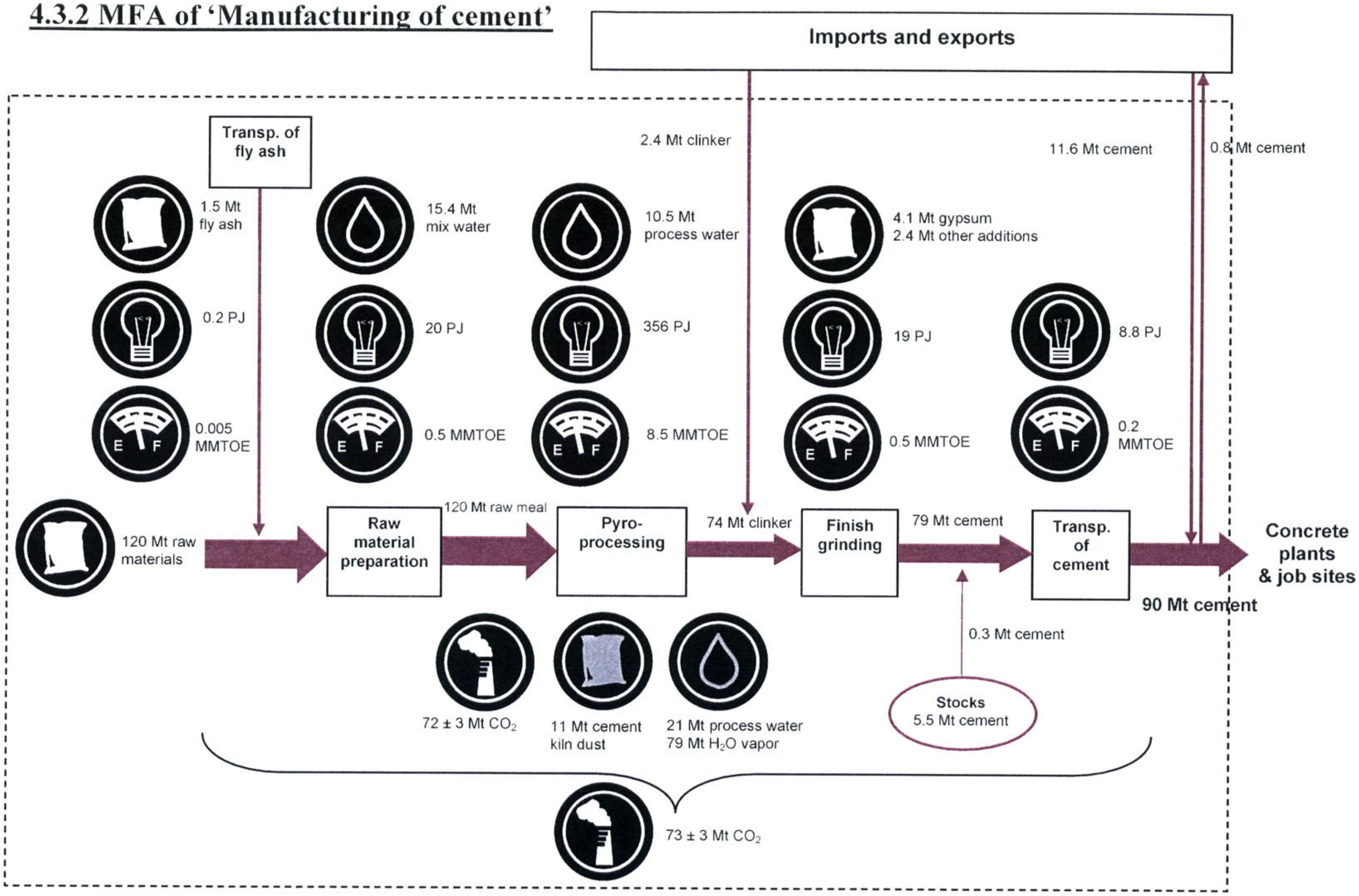
(iv) 'Raw meal preparation' – includes proportioning to desired mix and grinding to raw meal

(v) 'Pyroprocessing' - removing water from raw meal, calcining the limestone, clinkerization, clinker cooling and storage

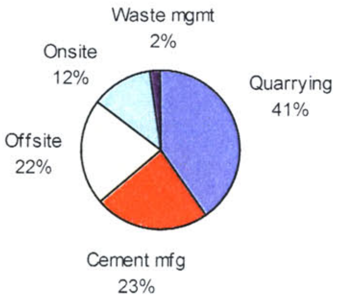
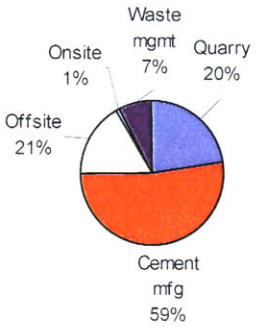
(vi) 'Finish grinding' - taking clinker out from storage, adding gypsum and grinding to a fine powder and conveying to storage

(vii) Transportation of
- fly ash as kiln feed
- domestically produced cement to concrete plant
- domestically produced cement to the site directly

4.3.2 MFA of 'Manufacturing of cement'



4.3.3 Summary

<table>
<tr><th></th><th>Input</th><th>Output</th></tr>
<tr><td>Materials</td><td>120 Mt raw materials
≡ 300,000 Boeing 747 planes
<i>[Total material throughput (including water) = 135 Mt]</i></td><td>79.3 Mt cement produced
≡ ~200,000 Boeing 747 planes
(90.4 Mt cement consumed)</td></tr>
<tr><td>Water</td><td>100 Mt water ≡ annual water consumption of 550,000 people (population of Denver, Colorado)

 </td><td>21.1 Mt effluent
78.8 Mt water vapor</td></tr>
<tr><td>Energy</td><td colspan="2">404 PJ or 5.10 GJ/t cement
≡ annual energy consumption of 24,525 people
Processing = 395.2 ± 38.7 PJ, Transportation = 9.0 PJ


Piechart is similar for fuel and CO_2 emissions.</td></tr>
<tr><td>Fuel</td><td colspan="2">9.3 MMTOE ≡ annual fuel consumption of 6 million automobiles</td></tr>
<tr><td>Emissions</td><td>-</td><td>At 909 kg CO_2/t cement (248 kg C/t),
73 Mt CO_2 ≡ annual CO_2 emissions of 1.6 mill automobiles</td></tr>
</table>

4.3.4 Details of MEFA

(a) Materials

In 1996, 79.3 million metric tons (Mt) of (hydraulic) cement is produced in 118 plants in 37 States and in Puerto Rico. Of this, 75.8 Mt is Portland cement (96% of total cement produced, including blended cement) and 3.5 Mt is masonry cement. Material inputs of ancillary materials such as filter bags, explosives, refractory, and cement bags are not included. Due to the high cost of cement, very minute quantities of cement is wasted (0.1% by mass of cement produced[18]) and is assumed negligible. In addition, it is assumed that the solid waste from cement manufacturing produced is predominantly in the form of cement kiln dust (CKD).

In the pyroprocessing stage, raw meal undergoes combustion to produce clinker, cement kiln dust or CKD (as the main form of solid waste produced) and CO_2. Based on higher precision and availability of data, estimates of CO_2 emissions and clinker produced are used in a mass balance to calculate the quantity of CKD generated. From Table 4.9, the 1996 CO_2 emissions emitted are close to 37.3 Mt, averaged among various national statistics. Subsequently, **11 Mt CKD** (= 120.0 – 71.7 – 37.3 Mt) was produced. This is verified to within reasonable range, as compared to estimates computed using aggregated figures and coefficients (see Table 4.5.) The PCA also provided an additional check by indicating that nearly 8 million tons CKD is recycled each year (PCA Factsheet).

Fly ash is either (i) added as a raw material into the raw or kiln feed before it enters the cement kiln, or (ii) ground together with clinker as an admixture to produce blended cement in the 'Finish grinding' stage or (iii) blended with cement in varying amounts.[19] It is also added into the concrete mix in concrete batching plants,[20] as (iv) an addition to Portland cement, or as (v) a supplementary cementing material (SCM) to replace cement. For more details on how additions and SCMs are used in concrete, see Chapter 5: Off-site production of concrete. Even up till the late 1990s, the usage of fly ash in cement plants had not been well-differentiated and virtually undocumented in concrete plants. This study estimates[21] that **0.2 Mt fly ash was used as an admixture, while 1.1 Mt was used as kiln/raw feed** in cement plants. This is equivalent to 9% of the cement mix (domestically produced) and is a reasonable estimate since fly ash corresponds to 9% of cement mix in 1991 (Environmental Building News, 1993). Another **5.9 Mt fly ash** is estimated to be used in concrete production. Other admixtures such as granulated blast furnace slag and other coal combustion products have not been included in this study because of the small quantities used (<1% by mass of raw materials for cement.)

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[18] Calculated using ATHENA coefficients for 'Solid Wastes due to Production of Cement'.

[19] ASTM (American Society for Testing and Materials) C595 defines two blended cement types: 1) Portland-pozzolan cement (Type IP) containing 15-40% pozzolan or 2) Pozzolan modified Portland cement (Type I-PM), containing less than 15% pozzolan.

[20] Technically speaking, adding fly ash into the cement/concrete mix in the concrete batching plant does not produce 'blended cement'. This is because unlike blended cements from cement plants, the blends made in concrete plants are not well-monitored and are not proprietary (Horst, 2001).

[21] For details of the estimates, see Appendix B: Notes on fly ash.

Table 4.4 Materials mass balance for cement manufacturing

	Raw material preparation (Mt)	Pyro-processing (Mt)	Finish grinding (Mt)	Apparent consumption (Mt)
Inputs				
Raw materials				
- Limestone & cement rock	105.7			
- Clay & shale	8.9			
- Sand & calcium silicate	2.2			
- Iron ore	1.5			
- Gypsum			4.1	
Fly ash	1.1		0.2	
Raw meal		119		
Clinker domestically produced			70.4	
Imported clinker			2.4	
Cement domestically produced				79.3
Net additions from stock				0.3
Imported cement				11.6
Other cement additions			2.2[a]	
Total water	15	100		
- Process water	15	85[b]		
- Slurry water		15		
Total	**135**	**219**	**79.3**	**91**
Outputs				
Raw meal	119.4			
Clinker domestically produced		72		
Cement consumed				
Cement domestically produced			79	
Exported cement				0.8
Cement kiln dust (CKD)		11		
CO_2		37		
Total water	15	100		
- Slurry water	15			
- Wastewater		21		
- Water vapor		79		
Total	**135**	**219**	**79**	**0.8**
Apparent consumption		**-**		**90**

Only materials in system boundary included.

(Sources: USGS Cement MCS 1996 and 2000 and Cement MYB 1996, US EPA, EIA, and author's calculations)

[a]: Unspecified. Computed through mass balance.

[b]: Assume all concrete plant water is used in the pyroprocessing kilns as cooling water.

Table 4.5 Total solid wastes produced for manufacturing 79.3 Mt cement in 1996

	Production (Mt)	**Recycled (Mt)**	**Other uses (Mt)**	**Disposed (Mt)**
Current study	**11.0**	**7.0**	**0.7**	**3.2**
Check based on annual aggregated figures				
AIA ERG, 1996; EPA, 1995	14.4	9.2	1.0	4.2
Van Oss & Padovani, 2002	12.5	8.4	4.1	-
Check based on coefficients				
PCA, LCI Portland Cement, 2002	5.5	1.4	-	4.1
ATHENA, 1999	3.5	2.5	-	1.0
Check: Buzzi Unicem, 2004	-	-	0.2	

- AIA ERG (1996): It is given that 12.7 Mt of CKD is produced in 1990 (EPA 1995), of which 64% is recycled, 7% for other uses and 29% disposed of. Scaling the 1990 cement production of 69.95 Mt cement to 79.3 Mt in 1996, 14.4 Mt CKD is produced assuming that the technology stays the same from 1990 and 1996.
- Van Oss & Padovani (2004): estimates that about CKD makes up 15-20% by weight of clinker output and typically about 2/3rd of CKD is returned to kilns while 1/3rd goes to landfills (majority) or sale. Assume 17.5% by weight of 71.7 mill t clinker produced, CKD produced weighs 12.5 Mt, of which 8.4 Mt is recycled and 4.1 Mt is disposed or sold.
- For calculations based on coefficients, see Appendix B: Table B 1.

Table 4.6 Estimates of waste materials used in concrete production in 1996

	Mass (Mt)		
	USGS Iron & steel slag MYB 1996	**American Coal Ash Association 2001-2003**	**Turner Fairbank/Federal Highway Administration 1996**
Fly ash	-	*11.0*	7.7
Blast furnace slag (total)	*1.97*	-	-
For concrete aggregates	*1.58*	-	-
For concrete products	*0.39*	-	-

- USGS Iron and steel slag MYB (1996): 1.39 Mt of air-cooled blast furnace slag (11.4% of 12.2 Mt total air-cooled blast furnace slag) used in concrete aggregate and 0.342 Mt used in concrete products (2.8%). Assuming that these percentages also hold for the 1.68 Mt of expanded blast furnace slag, 1.58 Mt blast furnace slag is used for concrete aggregates and 0.39 Mt used for concrete products.
- The blast furnace slag for concrete aggregates would not be included since it makes up about 0.3% of the total quantity of aggregates used in concrete production. Likewise, the blast furnace slag for concrete products is not included as it makes up about 0.5% of the apparent consumption of cement.

(b) Water

Approximately **100 Mt of water** is used as slurry water for wet-process kilns **(15 Mt)** and process water used in cooling machines and conditioning exhaust gases **(85 Mt).** All the slurry water was evaporated as water vapor in the kilns. It is assumed that 75% of the process water was used for cooling kiln exhaust gases and finish mill and 25% for non-contact cooling of bearings and cement. In other words, it is estimated that **64 Mt** water was evaporated and **21 Mt** exited as effluent. Though process water is continually recycled, it is assumed that the total amount of water entering the system eventually leaves the system as effluent. These estimates of water consumption are averages of the data in Table 4.7.

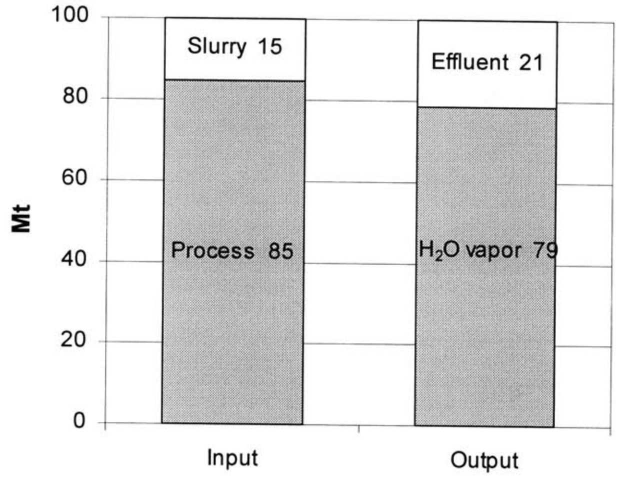

Figure 4.1 Water consumption of 'Manufacturing of cement' stage by input/output

Table 4.7 Estimates of water inputs and outputs for the cement manufacturing stage

	Input		**Output**	
	Slurry water (Mt)	**Process water (Mt)**	**H_2O vapor (Mt)**	**Effluent (Mt)**
PCA LCI of Portland Cement	16.4[a]	-	16.4[a]	-
AIA	14.8[b]	-	14.8[b]	-
ATHENA	-	158.6[c]	119.0[c]	39.6[c]
Van Oss & Padovani 2003	14.8[b]		14.8[b]	-
Check: Buzzi Unicem	7.5[c]	10.5[c]	15.4[c]	2.6[c]

[a]: For making slurry for wet process kilns (since 25.8% of domestically-produced clinker is produced by wet-process kilns, assume 25.8% of 79.3 Mt of domestic cement or 20.5 Mt domestic cement is from wet-process kilns.)

[b]: For making slurry for wet process kilns (USGS Cement MYB 1996: 25.8% of 71.7 Mt domestically clinker or 18.5 Mt domestic clinker.)

[c]: For 79.3 Mt cement domestically produced.

- For the water input and output coefficients used, see Appendix B: Table B2.
- Final estimate for slurry water: average of slurry water of PCA, AIA and van Oss & Padovani data.
- Final estimate for process water: average of ATHENA and Buzzi Unicem data.

(c) Energy

Accounting only for domestically produced clinker, the energy consumed for cement manufacturing (raw meal preparation, pyroprocessing and finish grinding) varies from 341 – 450 PJ and averages as **395 ± 39 PJ or 4.98 MJ/t cement** (4.50 – 5.47 MJ/t cement) (see Table 4.8.) The distribution of energy consumption by process is based on average percentages (see Figure 4.2 and Table B 3), which are similar to the 1994 energy consumption percentages given by Martin et al (1999).[22] The transportation energy is approximately **9.0 PJ** (average of the range 8.6 – 9.3 PJ). Subsequently, the **transportation energy required for cement is 8.8 PJ** and that for **fly ash is 0.2 PJ**. Therefore, the total energy used for the cement manufacturing stage is **404 ± 39 PJ.**

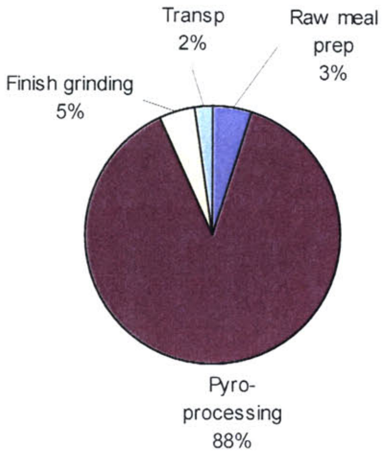

Figure 4.2 Energy consumption of 'Manufacturing of cement' stage by process (in percentages)

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[22] Scaling values from Martin et al (1999) to 1996 energy consumption levels: 16 PJ for 'Raw meal preparation', 363 PJ for 'Pyroprocessing' and 16 PJ for 'Finish grinding', i.e. a difference ranging from 4 – 7 PJ per stage (2 - 20%).

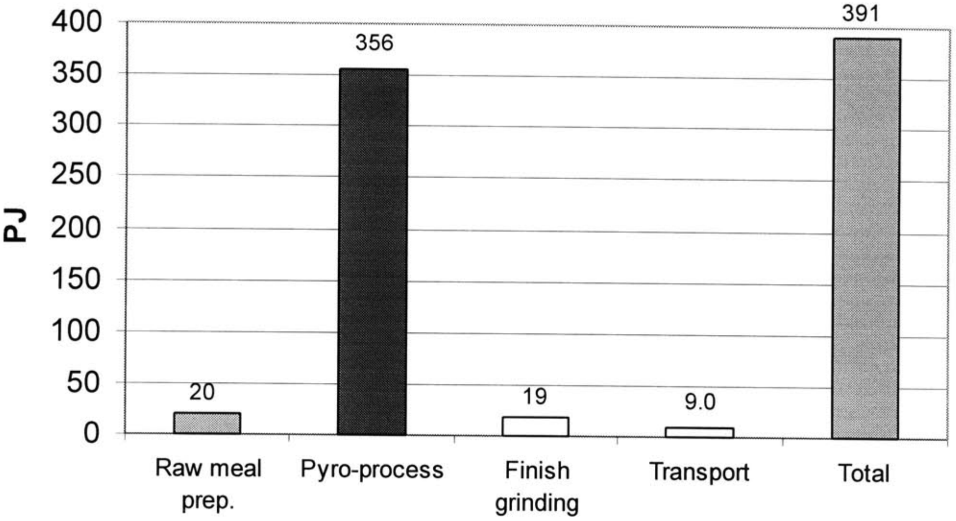


Figure 4.3 Energy consumption of 'Manufacturing of cement' stage by process

Table 4.8 Total energy consumed for domestic clinker and cement manufacturing

(All in PJ)	Raw meal prep.	Pyro-process	Finish grinding	Subtotal: cement mfg	Transp. of cement	Transp. of cement & fly ash
Based on national statistics						
EIA, 1998b (interpolated) (delivered energy)				355.3		
USGS MYB data (1996)						
Martin et al (1999) (estimate 1)	-	-	-	380	-	-
Martin et al (1999) (estimate 2)	-	-	-	450	-	-
Author's calculations	-	-	-	> 343.3'	-	-
Jacott et al (2003) (does not include electricity)				387.1		
Based on coefficients						
Van Oss & Pavodiani (2002)	-	-	-	425.0	-	-
PCA, LCI of Portland cement	6.3	378.3	21.4	406.0	-	-
PCA, LCI of Portland concrete	-	-	-	446.2	8.4	8.6
BEES	-	-	-	412.6	9.1	9.3
AIA; Hannon et al (1976)	-	-	-	-	27.3	-
ATHENA	30.6	309.0	15.1	354.6	26.2	-

(All estimates include electricity, otherwise indicated)

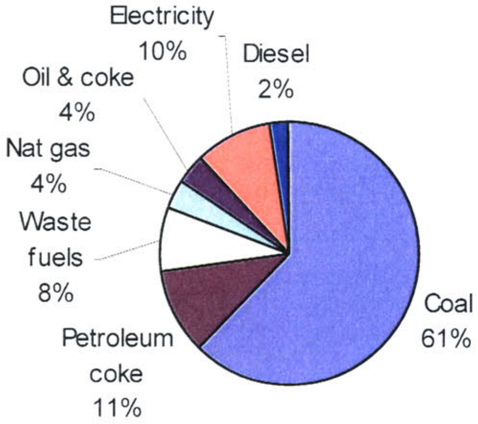
- EIA data: Delivered energy consumed by the cement manufacturing industry in 1998 = 356 trill BTU = 375.9 PJ for producing 83.9 Mt cement (95% of clinker is domestically produced) – as an underestimate to the actual primary and secondary energy consumed due to inefficiencies in energy generation and distribution. By interpolation, energy used in 1996 = 375.9 Mt / 83.9 Mt cement * 79.3 Mt cement = 355.3 PJ

- USGS data: Only quantities of fuel and electricity used are given. Depending on the energy content assignment for the different types of fuel, the computed energy consumption vary – as seen from the author's calculation and 2 calculations by Martin el al 1999.
- 70.4 Mt domestically-produced clinker and 2.4 Mt imported clinker are used to produce 79.3 Mt cement in the United States in 1996. By proportion, the amount of domestically-produced clinker is used to produce 76.7 mill t cement or 96.7% of the total cement produced. However, energy coefficients from PCA LCI Portland concrete and BEES does not allow for the distinction between domestically produced clinker and domestically produced cement (which could include imported clinker).
- Fly ash used in cement manufacturing in 1996 = 1.5 Mt.
- For coefficients used except for PCA LCI Portland Concrete, see Appendix B.
- For coefficients of PCA LCI Portland Concrete, see Appendix B.

(d) Fuel

The equivalence of approximately 404 PJ used in total for energy consumption (process and transportation) is **9.7 MMTOE** (million metric tons of oil equivalent), of which **9.5 MMTOE** is used for cement manufacturing processes and **0.2 MMTOE** is used for transportation of cement and fly ash. The different types of energy sources can be seen in Figure 4.4.

Figure 4.4 Fuel use of 'Manufacturing of cement' stage by fuel type



- *Based on author's calculations using 2001 figures for different fuel types (Hanle, 2004, Worrell & Galitsky, 2004) and USGS Cement MYB 1996 (which gives the allocation in various mass units).*
- *Diesel represents the total transportation energy: 91.1% cement transported by diesel truck, 7.2% diesel rail, 1.7% by diesel and residual oil barge, boat and others (USGS Cement MYB 1996).*

(e) Emissions

The total CO_2 emissions due to manufacturing of cement are estimated to be **73 ± 3 Mt**. The pyroprocessing stage (including fuel combustion and calcination) emitted approximately **72 ± 2.6 Mt CO_2 or 99% of the total emitted**, while transportation was responsible for **Mt CO_2**. To deal with the difficulty in determining CO_2 emissions from the lack of chemical analysis compilations for different raw material and fuel compositions (van Oss, USGS, 1996), aggregated figures specific to 1996 are used (see Table 4.9.) Hence, the CO_2 intensity is **909 kg CO_2/ t cement** or **248 kg C/t cement**.

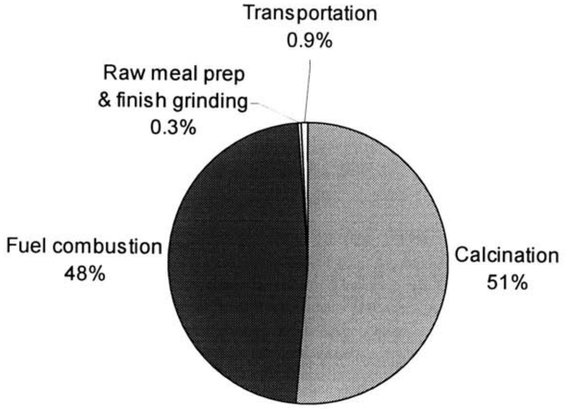


Figure 4.5 CO_2 emissions from the 'Manufacturing of cement' stage by process

- For total emissions, see Appendix B: Table B 13. For coefficients, see Appendix B: Table B 14.

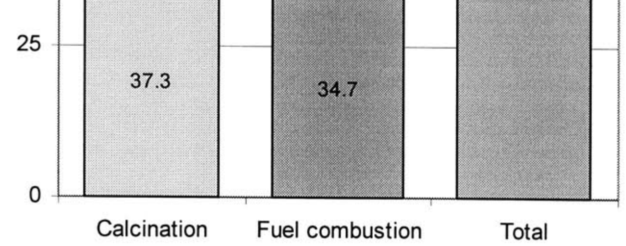


Figure 4.6 CO_2 emissions from the pyroprocessing stage

- For estimates used, see Table 4.9.

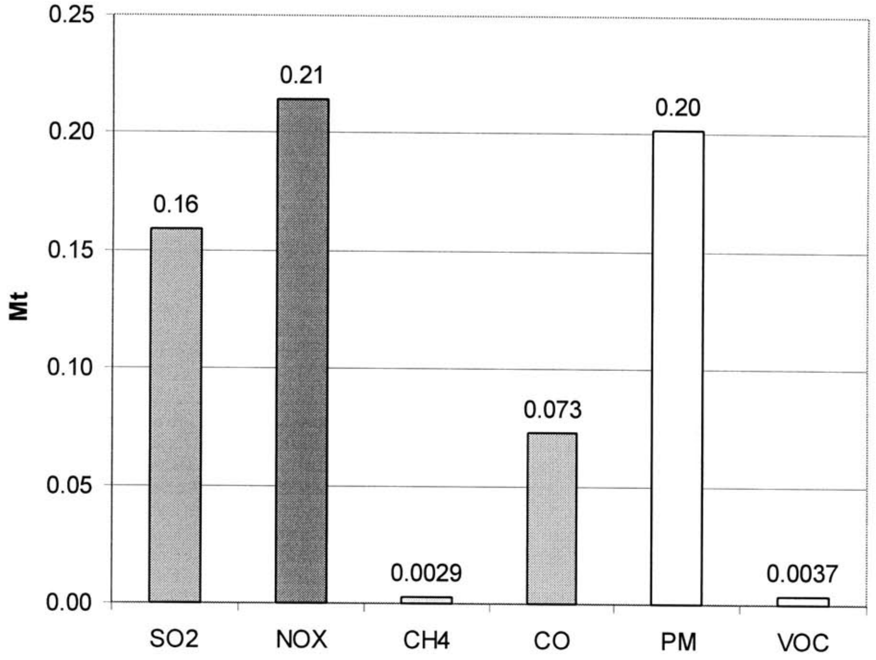


Figure 4.7 Total emissions from 'Manufacturing of cement' stage

- Based on the fuel mix given in the PCA LCI of Portland concrete, which is pretty similar to the fuel mix defined in Figure 4.4. The PCA fuel mix has a lower coal content and higher pet coke and natural gas.)
- Includes raw meal preparation, calcination, fuel combustion & finish grinding.
- For total emissions, see Appendix B: Table B 13. For coefficients, see Appendix B: Table B 14.

Table 4.9 Estimates of total CO_2 emissions from pyroprocessing

	CO_2 (Mt)		
	Total	**Calcination**	**Fuel combustion**
Based on aggregated figures			
Hanle, EPA (2004)	68.7	37.1	31.6
EIA (2000)	74.1	37.0	37.1
Jacott et al (2003)	70.2	37.1	33.1
USGS cement MYB (1996)	72.5 (70-75)	38 (36-40)	34.5 (34-35)
Martin et al (1999)	74.7	37.4	37.4
Based on coefficients			
EPA AP-42 (1994)	65.7	35.2	30.5
PCA (2002)	63.1	-	-
ATHENA	54.6	35.1	19.5
AIA (1996)	76.2	35.0	42.2

All aggregated figures are for specific to 1996.

- To convert Mt of CO_2 to Million Metric Tons Carbon Equivalent (MMTC) – multiply by 12/44.
- (Hanle, EPA 2004): Various sources are cited in work – USGS, U.S. Department of Interior, EPA). Process-related CO_2 (which includes CKD) is taken as CO_2 from calcination.

- (EIA 2000): CO_2 emissions from energy are taken as CO_2 emissions from fuel combustion (10.1 MMTC). CO_2 emissions from industrial processes are taken as CO_2 emissions from calcination (10.13 MMTC = CO2 emissions from clinker production (9.91 MMTC) + masonry cement (0.02 MMTC) + cement kiln dust (0.20 MMTC)).
- Jacott et al 2000: Emissions data (except for CO_2) are from U.S. EPA, AIRSDATA, National Emissions Trend Database, 1996; query run on February 11, 2003 and U.S. EPA's Toxic Release Inventory, February 12, 2002 (www.epa.gov/triexplorer).
- EPA AP-42: Applying PCA LCI of Portland cement percentages by type of kiln and assuming 71% kilns are coal–powered (from Hanle 2004; Worrell & Galitsky 2004), the AP-42 coefficients (per Mt) are multiplied by 70.4 Mt clinker domestically produced. [500 kg CO_2/metric ton for calcination, 432.963 kg CO_2/metric ton for fuel combustion]. The reason being that multiplying by 90.3 Mt cement produced would over-exaggerate the estimate.
- PCA: Weighted average fuel combustion and calcination coefficient: 896.2 kg/metric ton cement * 70.4 Mt cement
- ATHENA: Average fuel combustion coefficient: 277.2 kg/metric ton cement * 70.4 Mt cement Weighted average calcination coefficient: 498.334 kg/metric ton cement * 70.4 Mt cement
- AIA: calcination coefficient of 452 kg CO_2/ short ton cement [498.2 kg CO_2/metric ton]: multiplying with 70.4 Mt clinker gives 35.0 Mt CO_2, with 79.3 Mt cement 39.5 Mt CO_2. Fuel combustion coefficient as the average of 450-640 kg CO_2/ short ton cement [600.7 kg CO_2/metric ton]: multiplying with 70.4 Mt clinker gives 42.2 Mt CO_2, with 79.3 Mt cement 47.6 Mt CO_2.

4.4 Preliminary conclusions

1. Through mass balances, it is found that an estimated **11 Mt of CKD** was produced in 1996. In addition, approximately **1.3 Mt of fly ash was used in cement plants** as admixtures and kiln feed and **5.9 Mt in concrete plants** as SCM or additions.
2. Approximately **15%** of the water used in cement plants was used to produce wet slurry for wet process kilns. The remaining 85% was used for cooling kiln exhaust gases and for non-contact cooling of bearings and cement.
3. It is found that roughly **395 ± 39 PJ** was used in cement manufacturing (raw meal preparation, pyroprocessing and finish grinding) or **4.98 MJ/t cement**. Including the **9 PJ** consumed for transporting cement and fly ash, the total sums up to **404 PJ ± 39 PJ.**
4. The total emissions from cement manufacturing and transportation emitted are estimated to be **73 ± 3 Mt** or **909 kg CO_2/t cement.**

Overall, the literature of the raw materials consumed and CO_2 emissions produced by the cement industry is widely available. On the other hand, literature on water consumption and CKD generation is fairly limited. The increasing use of SCM and other waste products in cement manufacturing presents an interesting trend of cement being replaced over time. A smaller percentage of cement in the concrete mix, as supplemented by SCM and other waste products, can signify a relative increase in concrete production and cause implications such as an increase in aggregates extraction. Therefore, a clearer distinction of how SCM and other waste products flow to end-uses (i.e. kiln feed versus SCM and additions) and types of facilities (cement versus concrete plants) is essential to address the dynamics between cement and concrete production. This chapter has presented how cement is produced. The next chapter presents how ready-mixed concrete and concrete products are produced from cement, aggregates and water in off-site concrete plants.

CHAPTER 5 OFF-SITE PRODUCTION OF CONCRETE

5.1 Introduction

Cement (10-15%) and any supplementary cementitious materials (SCM) are mixed with aggregates (60-75%), water (15-20%) and admixtures (<1% of cement mass) to form concrete. SCMs or mineral admixtures act as cement replacements (of up to 1:1 ratio) due to their pozzolanic nature, which is the ability to become cementitious under reaction with lime/calcium hydroxide. Examples include fly ash, silica fume, and ground granulated blast-furnace slag. Admixtures (mineral and chemical) control concrete properties and performance (e.g. entraining admixtures, water-reducing admixtures, accelerators and superplasticizers). Similar to the assumption made in the PCA LCI of Portland Concrete Admixtures based on SETAC guidelines,[23,24] admixtures are not included in this study since they are used in minute quantities. However, it is debatable as to whether admixtures offgas during the use phase. Depending on the concrete type, these ingredients are either sent off-site to concrete plants for processing or directly to the job site for use. This chapter will focus on off-site production of concrete while the next chapter will deal with on-site production of concrete.

In general, concrete ingredients are first batched or proportioned to specified compositions by weight. Then, they are mixed together with water to form concrete. Depending on the application, the concrete might be poured into molds or in between wood or steel formwork for predetermined forms (e.g. blocks and walls). Next, the concrete is cured under moist conditions between 10-24°C for cement hydration to occur. In other words, both C_3S (alite) and C_2S (belite) hydrate to form tricalcium silicate hydrate gel/tobermorite plus lime in a typical reaction[25]:

$$2C_3S + 6H \text{ (water)} \rightarrow C_3S_2H_3 \text{ (tobermorite gel)} + 3CH \text{ (lime)}$$

C_3S hydrates quickly and imparts early strength, while C_2S behaves the opposite. The tobermorite and other calcium silicate hydrates act as a binder for the aggregates. Over time, as C_2S also gets hydrated, the concrete gains more strength. For general construction, concrete must cure for at least three days (typically seven days) to gain sufficient compressive strength.

Among the ingredients sent for off-site processing, the majority are used to produce ready-mixed concrete in concrete batching or central mix plants. The remaining

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[23] SETAC guidelines state that inputs, (i) of less than 1% of total mass of product, (ii) which do not release toxic emissions and (iii) do not require significant emissions, need not be included (PCA LCI of Portland Concrete, 2002).

[24] It is verified that since the admixtures are chemically bonded in the concrete, they are not likely to release emissions or effluent contamination (PCA LCI of Portland Concrete). Other literature states that admixtures do offgas minute amounts of formaldehyde into the indoor air quality.

[25] See Chapter 3 for the longhand notation of the chemical compounds.

ingredients are sent to concrete prefabrication plants. The end-products include concrete bricks or blocks (e.g. concrete masonry units or CMUs), precast structural and architectural elements (e.g. beams, columns, hollow-core planks, hollow decks and wall panels) and pipes.

5.2 Off-site production of concrete

Based on PCA LCI of Portland Concrete, the manufacturing processes of ready-mixed concrete and concrete products are further described below:

(i) Production of ready-mixed concrete

The slight differences between concrete batching plants and central mix plants are presented in Figure 5.1. About 75% of the ready-mix plants are concrete batching plants, which perform only the batching and proportioning process. Firstly, ingredients from stockpiles and water are batched by weight, and then gravity-fed into trucks via weigh hoppers. Next, the concrete slurry is transit-mixed during transport before being poured upon arrival at the job site. The other 25% of the ready-mix plants are central mix facilities, where the ingredients are batched and mixed before being poured into open bed dump trucks or agitator trucks for transport to the job site. At times, the concrete is partially mixed (also known as shrink mixed) in the plant and then completely mixed in truck mixers during transport (EPA AP-42 Section 11.12, *Concrete Batching* cited in PCA LCI of Portland Concrete, 2002).

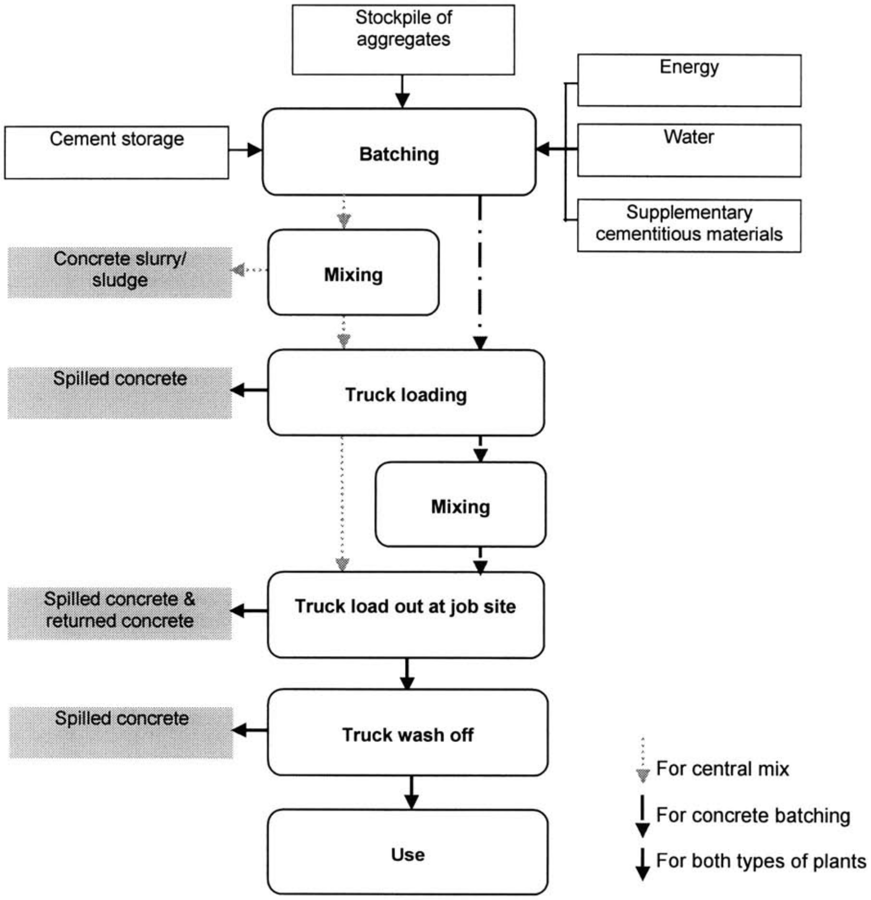


Figure 5.1 Process flowchart of ready-mixed concrete batching and mixing
(Modified from PCA LCI of Portland concrete, 2002, Souwerbren, 1996)

While cement wastages are kept to a minimum during handling in concrete plants, 2 – 5% of the concrete produced becomes solid waste on average (PCA PCI of Portland Concrete, 2002). Approximately, 90% of the solid waste, as returned materials in trucks after use at the job site, is recycled due to high landfill costs ($28-$55/ metric ton) (PCA LCI of Portland Concrete, 2002). Some methods include:

(i) first windrowing and hardening the slurry, then crushed for use as fill or aggregate
(ii) applying hydration control agents and mixing into a new batch of concrete
(iii) pouring into forms such as blocks
(iv) paving plant property
(v) reclaiming and reusing the slurry

Subsequently, the trucks would have to be washed off and washed out. Not surprisingly, concrete plants typically consume significant amounts of water. In general, transit mixers transporting dry materials tend to require more wash off water and they are more frequently used in rural areas with longer haul distances to the job site.

Fugitive emissions of particulate matter in wind erosion of aggregate stockpiles, transfer of aggregates, truck loading and mixer loading may be causes for environmental concerns. This can be controlled by water sprays, enclosures and hoods (EPA AP-42 Section 11.12, *Concrete Batching* cited in PCA LCI of Portland Concrete, 2002).

(ii) Prefabrication of concrete products

The prefabrication of concrete blocks and precast concrete are similar. In place of molds for block production, form work is used instead. Figure 5.2 shows the processes involved for each type of prefabrication.

Among the different shapes and sizes of concrete blocks, the 8 x 8 x 16 in (0.2 x 0.2 x 0.4 m) concrete masonry unit (CMU) is the most dominant. The production of concrete blocks is similar to the central-mix ready-mixed concrete plant, except that there are additional processes of molding and curing. In 24-hour cycles, very dry, no-slump concrete (with no coarse aggregates used) is placed in molds. Next, the molds are removed; the concrete undergoes accelerated curing at ambient temperatures or higher temperatures in kilns (up to 90°C). Solid waste is generated in the form of damaged masonry units, which are crushed and recycled as aggregate or fill. Unlike the central-mix plant, concrete block and precast concrete plants do not require water for truck wash off and wash out. In addition, pipes are noted as a separate category from precast concrete in this MEFA, though they are a form of precast concrete. This is done to remain consistent with the different end-uses of cement defined in the USGS Cement MYB.

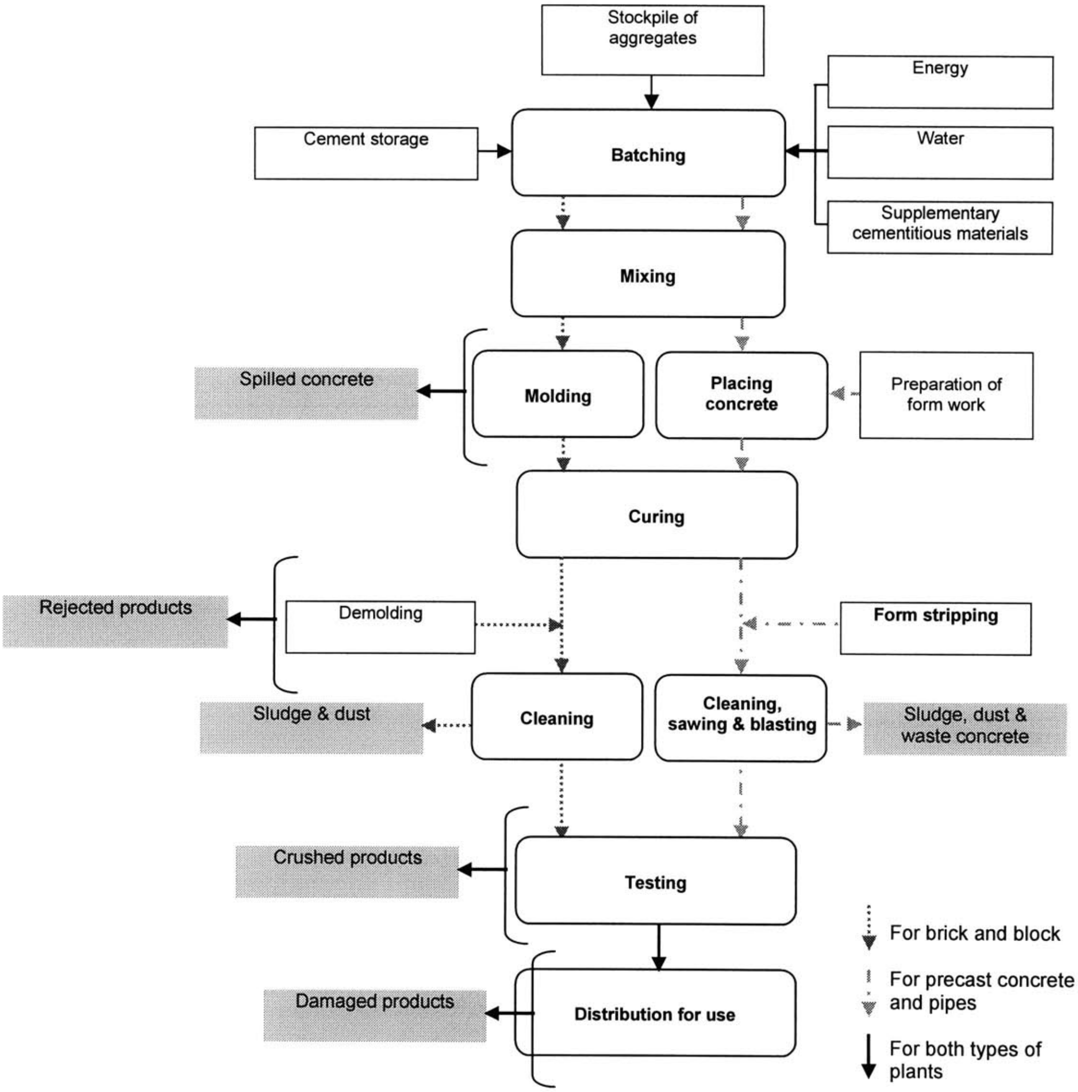


Figure 5.2 Process flowchart of prefabrication of concrete products
(Modified from PCA LCI of Portland concrete, 2002, Souwerbren, 1996)

5.3 MFA results

5.3.1 System boundaries

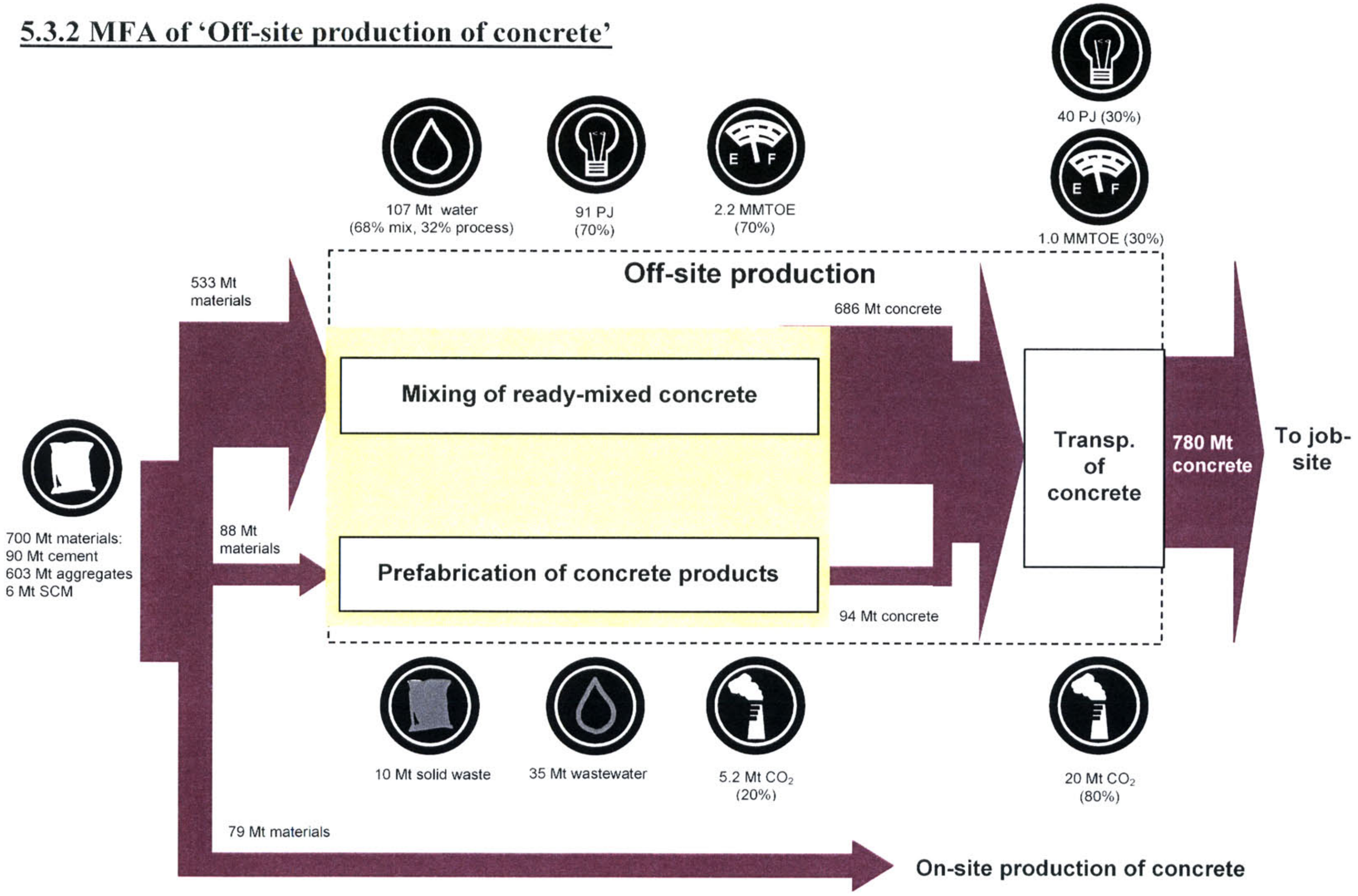
The processes included in the system boundaries are:

(viii) Production of 'Ready-mixed concrete' in concrete batching plants, central mix plants and truck mixers

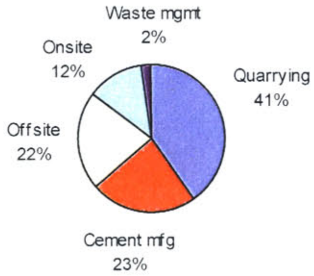
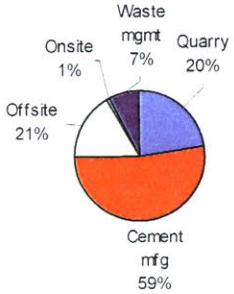
(ix) Prefabrication of 'Concrete products' (i.e. bricks and blocks, precast concrete, and pipes).

(x) Transportation of
- ready-mixed concrete from concrete plant to the site for use
- finished concrete products from concrete plant to the site for use

5.3.2 MFA of 'Off-site production of concrete'



5.3.3 Summary

	Input	Output
Materials	**716 Mt** solid materials (includes 14% recycled materials) ≡ **7,200 Empire state buildings** *[Total material throughput (including water) = 824 Mt]*	**780 Mt** concrete produced ≡ **7,800 Empire state buildings** & **10 Mt** solid waste disposed = **100 Empire state buildings** (assuming 90% recycling)
Water	**107 Mt** water ≡ annual water consumption of **1.5 mill people** (equivalent to Philadelphia, PA population today) 	**35 Mt** wastewater  **Total waste generated for this stage**  **Total waste disposed for this stage**
Energy	**131 PJ** or **0.17 GJ/m^3 concrete** ≡ annual energy consumption of **3.2 million people** in 1996 (= Chicago city, IL & Arlington city, TX population today combined) Processing = **91 PJ**, Transportation = **40 PJ**  Piechart is similar for fuel and CO_2 emissions.	
Fuel	**3.2 MMTOE** ≡ annual fuel consumption of **2.3 million automobiles**	
Emissions	-	**25 Mt CO_2** ≡ annual CO_2 emissions of **0.6 mill automobiles** or **32 kg CO_2/m^3 concrete**

5.3.4 Details of MEFA

(a) Materials

Approximately 90% of the hydraulic cement was sent to off-site concrete plants to be batched and mixed into ready-mixed concrete (76%), and prefabricated into concrete products (11%). This results in the production of **approximately 780 Mt concrete (339 mill m^3)** in 1996, of which **686 Mt is ready-mixed concrete** and **94 Mt concrete products** (see Figure 5.3). In other words, seven times more ready-mixed concrete is produced as compared to concrete products. Details of mass flows by concrete type are shown in Figure 5.5.

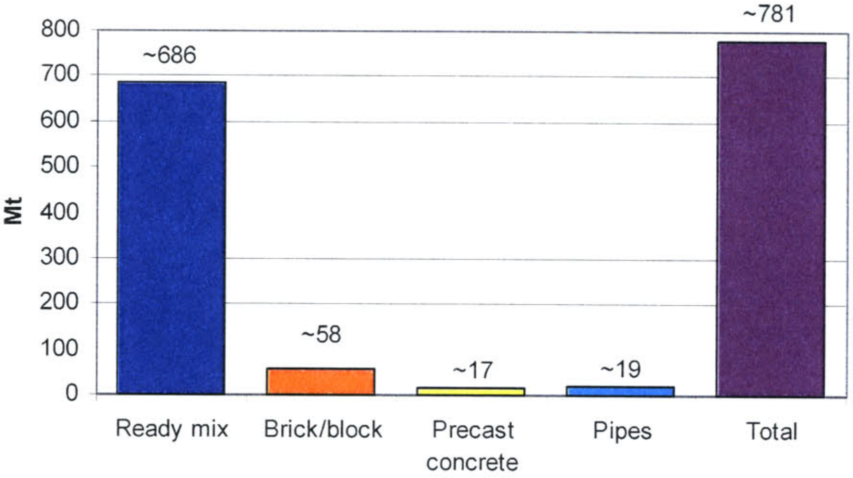


Figure 5.3 Breakdown of concrete produced in off-site concrete plants by type (in values)

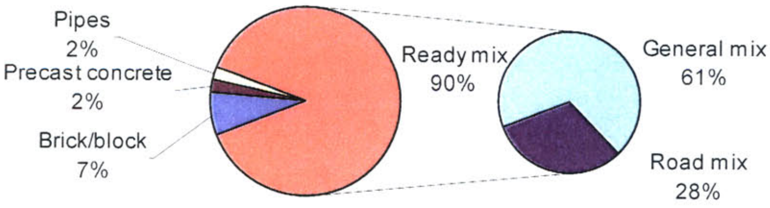


Figure 5.4 Breakdown of concrete produced in off-site concrete plants by type (in percentages)

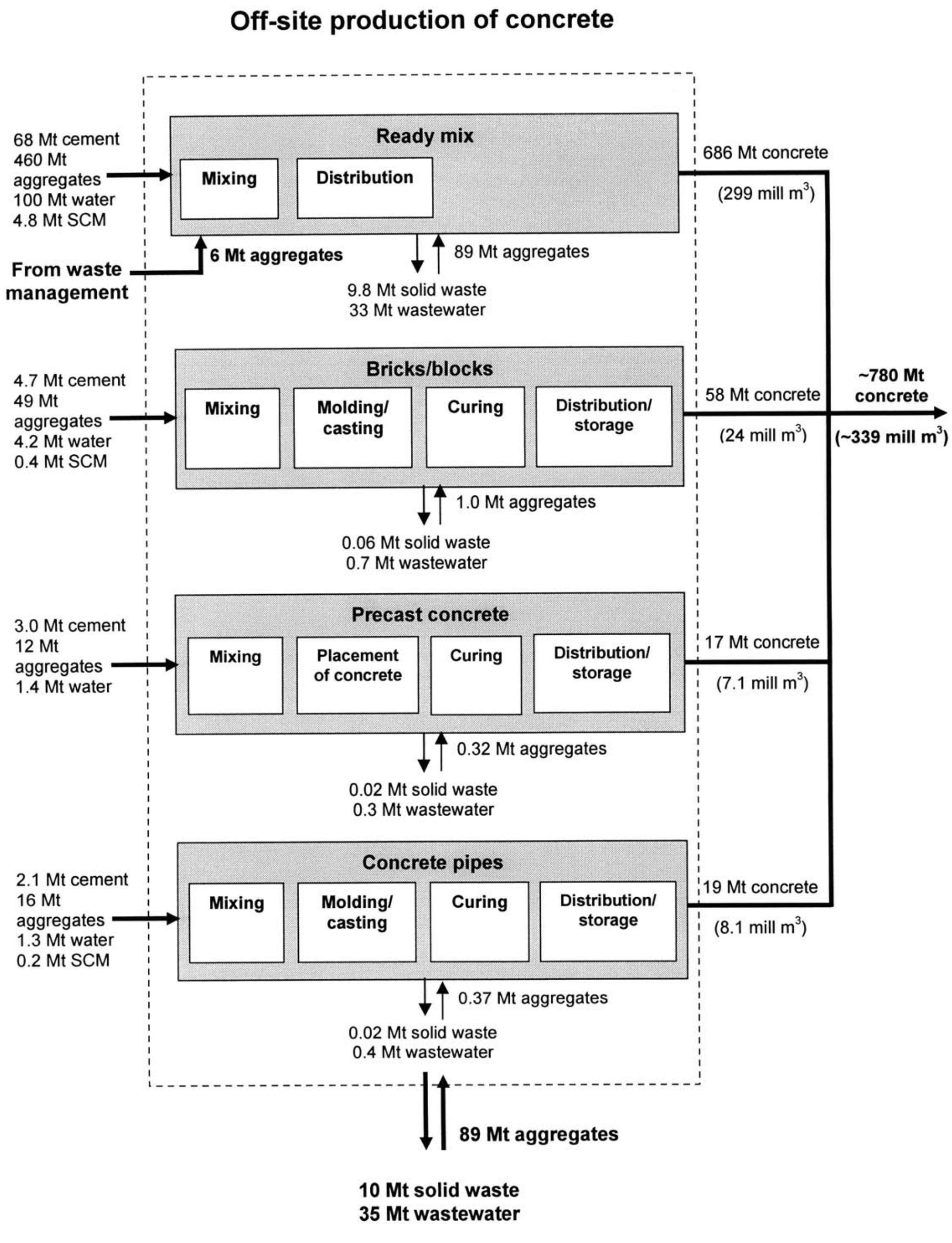


Figure 5.5 Detailed mass balance of 'Off-site production of concrete' stage

Table 5.1 shows the quantities of raw materials required for each concrete type, as given by the PCA LCI of Portland Concrete with modifications on the fly ash requirements. As shown in Chapter 3, 5.9 Mt fly ash was used in concrete production as supplementary cementitious materials (SCM) and admixtures (or about 8% of cement used for off-site production). Based on the following assumptions, it is estimated that 0.0752 metric ton of fly ash/metric ton of cement was used for applicable cement types (or 7.5% of cement by mass).

Facts:	**Assumptions for current study:**
Use of admixtures is relatively small (typically make up <1% by mass of cement[26]).	1) Majority of fly ash is used as SCM to replace cement instead of as admixtures.
Blended cement are used for general construction and is not recommended for structures which require high early strength	2) Fly ash is only used for concrete which has strength of less than 35 MPa. In other words, it is assumed that fly ash is not used in 35 MPa ready-mixed concrete, precast concrete and other infrastructure.
It is recommended that fly ash is not added to blended cement, since it already contains fly ash.	3) No fly ash is added during the use of the 0.8 Mt of blended cement (see Chapter 3).

In addition, the solid waste produced is computed using coefficients from PCA LCI of Portland Concrete and ATHENA (see Table 5.2).

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[26] Minute quantities of other types of SCM and admixtures (e.g. granulated blast furnace slag) are also used. Again, they have been excluded since they typically make up <1% by mass of cement.

Table 5.1 Materials mass balance for off-site production of concrete

	Total	Ready-mixed concrete			Concrete products			
		General mix	Road mix	Subtotal	Brick/ block	Precast concrete	Pipes	Subtotal
Inputs (Mt)								
Cement	**~78**	45	24	**68**	4.7	3.0	2.1	**10**
Aggregates	**~537**	346*	115*	**460***	49*	12*	16*	**77***
Total water	**~107**	53	47	**100**	4.2	1.4	1.3	**6.9**
- Mix water	~72	29	37	66	3.5	1.1	0.9	5.5
- Process water	~35	23	10	33	0.7	0.3	0.4	1.4
SCMs (Supplementary cementitious materials)	**~5.3**	3.0	1.8	**4.8**	0.4	-	0.2	**0.5**
Recycled waste as aggregates**	**~96**	57	37	**95**	1.1	0.32	0.37	**1.9**
Materials consumed in concrete* **	**~790**	481	215	**~696**	~58	~17	~19	**~94**
Total inputs	**~824**	**~504**	**~225**	**~728**	**~59**	**~17**	**~20**	**~96**
Outputs (Mt)								
Concrete produced	**~780**	**472**	**214**	**~686**	**~58**	**~17**	**~19**	**~94**
Total waste	**~45**	29	14	**44**	0.8	0.3	0.4	**1.5**
- Solid waste (disposed)	~10	6.0	3.8	9.8	0.06	0.02	0.02	0.09
- Wastewater	~35	23	10	33	0.7	0.3	0.4	1.4
Total outputs	**~824**	**~501**	**~228**	**~730**	**~59**	**~17**	**~19**	**~95**

(Source: Author's calculations using 1996 USGS Cement MYB and MCS, PCA LCI of Portland concrete & ATHENA)

Only materials in system boundary included.

*: Net of aggregates from recycled waste

**: Includes 6 Mt of recycled aggregates from the waste management of concrete; assume 100% recycling efficiency (see Chapter 7).

***: Includes cement, aggregates (virgin/extracted and waste), mix water and SCM.

- Totals do not add up due to independent rounding.
- Assuming that all recycled waste is used as aggregates.

The total amount of solid waste generated during the off-site production was **approximately 106 Mt** (about 15% of total solid materials input which includes waste materials). It is assumed that the recycling rate is 90%[27]. The recycling rate is high due to high landfill costs of $28 - $55/metric ton (PCA LCI of Portland concrete, 2002). In addition, it is assumed all of the solid waste gets recycled into aggregates (coarse and fine) for production of new concrete in this study. This is a fair assumption since at least 87% of the recycled solid waste is in the form of returned concrete (see Table 5.2.) To incorporate the additional **6 Mt** of recycled aggregates produced from the waste management stage (see Chapter 7), the author assumes that it is used in the production of ready-mixed concrete with an assumed 100% recycling efficiency. Ready-mixed concrete production accounts for 98% of the total solid waste generated during off-site production and consist of returned concrete, truck washout and mixer washout (see Figure 5.6). The production of concrete products accounts for the remaining 2%, since minimal waste is generated from the consolidated mixing and casting processes at one location.

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[27] The derivation of the quantity of solid waste recycled is based on the assumptions made in PCA LCI of Portland Concrete (recycling rates of 90 – 95%, depending on concrete type).

Per volume, ready-mixed concrete production generates almost six times more solid waste than concrete products. Ready-mixed concrete production requires truck mixers for transit mixing, which require additional cleaning. In addition, returned concrete slurry contributes heavily to solid waste generation, whereas the handling of raw materials, water and effluents are consolidated at one facility for precast concrete production.

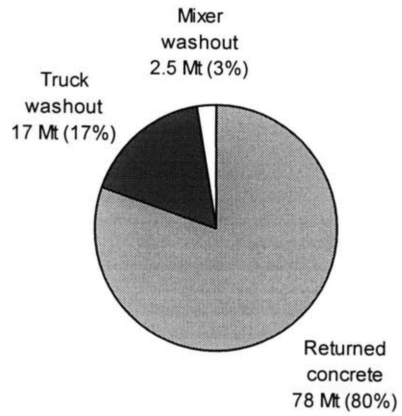


Figure 5.6 Breakdown of solid waste generated from ready-mixed concrete production

Table 5.2 Total solid waste for 'Off-site production of concrete' stage

Solid waste (Mt)	**Ready-mixed concrete***	**Bricks/ blocks**	**Precast concrete**	**Concrete pipes**	**Total**
Estimate 1 (PCA LCI of Portland concrete, 2002)					
Returned concrete	38	-	-	-	-
Truck washout	8.2	-	-	-	-
Mixer washout	1.2	-	-	-	-
Subtotal	**48**	-	-	-	-
Waste recycled	43	1.4	0.41	0.47	-
Waste disposed	**4.9**	**0.075**	**0.021**	**0.024**	-
Estimate 2 (ATHENA)					
Waste disposed	**14.8**	**0.038**	**0.013**	**0.015**	-
Current study figures:					
Total waste generated	**~99**	**~1.2**	**~0.34**	**~0.39**	**101**
Waste disposed (average)	**9.9**	**0.056**	**0.017**	**0.019**	**10**
Waste recycled[a]	**89 (90%)**	**1.1 (95%)**	**0.32 (95%)**	**0.37 (95%)**	**91**
Recycled aggregates[b]	**6**	**-**	**-**	**-**	**-**
Total recycled aggregates	**95**	**1.1**	**0.32**	**0.37**	**97**

* Includes general mix and road mix.

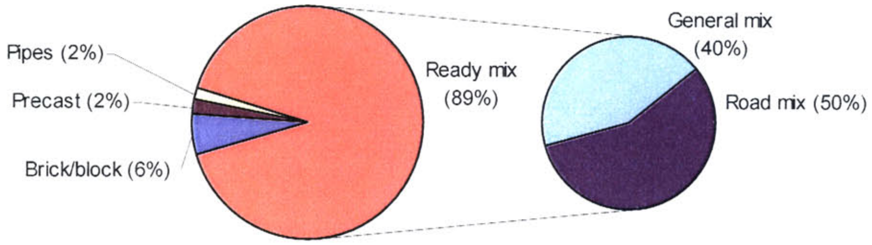
[a]: From production of concrete.

[b]: From waste management of concrete (see Chapter 7). Assumption: recycled aggregates used in new cement concrete production is used in ready-mixed concrete.

- Coefficients used are in Appendix C: Table C1.

(b) Water

Approximately **107 Mt of water** was used. Two-thirds was used as mix water for cement hydration **(72 Mt or 67%)** and one-third as process water used in washing mixers, forms and tools **(35 Mt or 33%).** Though process water is continually recycled, it is assumed that the total amount of water entering the system eventually leaves the system as **34 Mt** of effluent. Again, it can be seen that ready-mixed concrete produces six times more wastewater than concrete products. In addition, as noted in Figure 5.7, water use for road mix is **2.5 times greater** than for general mix per unit volume because of a higher water-to-cement ratio required (1.4 versus 0.68).



- Includes mix water and process water.

Figure 5.7 Total water input of 'Off-site production of concrete' stage by concrete type

Table 5.3 Total water consumption of the 'Off-site production of concrete' stage

Type	Input (Mt)			Output (Mt)				
	Mix water	Process water[a]	Total influent	Truck wash off[b]	Truck/equip. wash out[b]	Misc.[b]	Total effluent	Embodied water
Ready-mix	66	33	99	20	4.5	8.8	33	66
- General	29	23	52	14	3.1	6.1	23	29
- Road	37	10	47	6.1	1.4	2.7	10	37
Concrete products	5.5	1.4	6.9	-	1.4		1.4	5.5
- Brick/block	3.5	0.7	4.2	-	-	0.7	0.7	3.1
- Precast	1.1	0.3	1.4	-	0.3		0.3	1.1
- Pipes	0.9	0.4	1.3	-	0.4		0.4	0.9
Total	**72**	**35**	**107**	-	-		**35**	**72**

(Source: Author's computations based on data from PCA LCI of Portland Concrete and ATHENA)
'Mix water' = concrete mix water, 'Process water' = water for washing mixers, forms and tools,
'Embodied water' = water used for cement hydration to form cement binder for concrete.

[a]: Process water is the average of PCA LCI of Portland Concrete and ATHENA coefficients.

[b]: Based on PCA LCI of Portland Concrete coefficients.

- For coefficients, see Appendix C: Table C2.

(c) Energy

The total energy required for the batching/prefabrication and transportation is approximately **131 PJ.** Of this, **70%** (91 PJ) was used **for mixing and prefabrication** and **30% (40 PJ) for transportation**. The processing energy required for ready-mixed concrete, precast concrete and pipes are similar at 0.245 – 0.247 GJ/m^3 concrete. Interestingly, concrete brick/blocks are almost twice as energy-intensive per unit volume. The energy accounted for the additional curing process of concrete blocks in kilns in the PCA LCI of Portland Concrete is too small to account for the variance. One possible factor might be due to the different technologies used in concrete block plants.

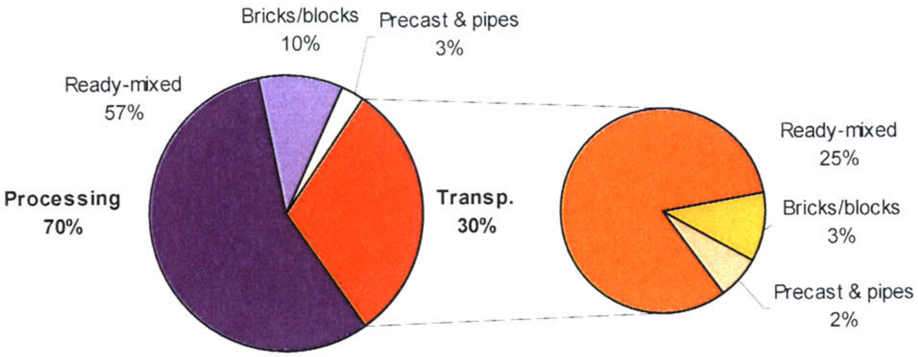


Figure 5.8 Energy consumption of 'Off-site production of concrete' stage by subprocess

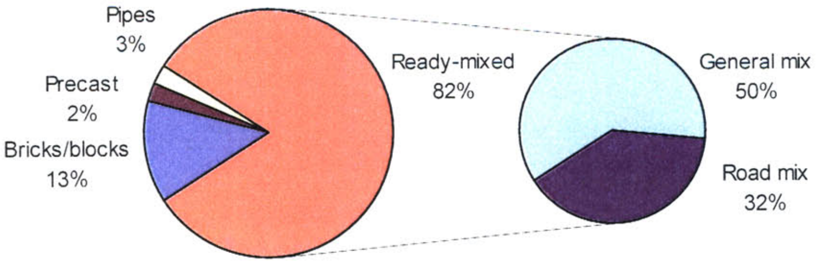


Figure 5.9 Energy consumption of 'Off-site production of concrete' stage by product

Table 5.4 Total energy used for 'Off-site production of concrete' by process

	Batching and prefabrication (PJ)	Transportation (PJ)	Total energy (PJ)
Ready-mixed concrete	74*	33	107
- General mix	45	20	65
- Road mix	29	13	42
Concrete products	17	7.2	24
- Bricks/blocks	13	4.4	18
- Precast concrete	1.8	1.3	3.1
- Pipes	2.0	1.5	3.5
Total	**~91**	**~40**	**~131**

*: Use average of energy computed from estimate 1 (74.5 PJ) and estimate 2 (73.2 PJ).

Table 5.5 Energy use coefficients of 'Off-site production of concrete' by product

	Batching and prefabrication (GJ/m^3 concrete)	**Transportation to job site** (GJ/m^3 concrete)
Ready-mixed concrete (estimate 1)	0.247	0.108[a]
Ready-mixed concrete (estimate 2)	0.242[b]	-
Bricks/blocks	0.536[c]	0.1805
Precast concrete	0.247	0.1805[d]
Pipes	0.247[d]	0.1805[d]

[a] Author's best estimate based on AIA ERG (1996), PCA LCI of Portland Concrete (2002), BEES (2002) and Vold & Rønning values (1995).

[b] Weighted average of ATHENA values by author's estimations of 20 MPa, 30 MPa and 35 MPa ready-mixed concrete percentages.

[c] Average of PCA LCI Portland Concrete (0.314 GJ/m^3 concrete, which includes curing) and ATHENA (0.757 GJ/m^3 concrete).

[d] Assume transportation energy for precast concrete and pipes are similar to bricks/blocks.

[e] Assume prefabrication of pipes similar to precast concrete.

- Ready-mixed concrete (estimate 1) is from PCA LCI Portland Concrete, for central mix plant.
- Ready-mixed concrete (estimate 2) is from ATHENA. Assume production of 35 MPa ready-mixed concrete is similar to that of 60 MPa listed in ATHENA (since the ATHENA coefficients are not scaled proportionally by the strength of the concrete).
- Transportation of brick/block:
  (Hannon et al, 1976 cited in AIA ERG 1996) For a typical concrete masonry unit to the job site = 2,803 Btu/unit = 0.00296 GJ/unit = 0.1805 GJ/m^3.
- Transportation of ready-mixed concrete (requires energy for mixing during transportation, but travel less distance – less than 2 hours; compared to other concrete types):
  PCA LCI Portland Concrete, 2002 & BEES, 2002: Assuming transportation energy and distances of ready-mixed concrete and concrete products similar to aggregates, average transportation coefficient = 0.103 GJ/m^3 concrete (does not account for mixing of ready-mixed during transportation).
  Vold & Rønning, 1995: Transportation energy for concrete = 0.040 GJ/m^3 (seen as a little too low compared to brick/block transportation)
  The average of the three estimates is taken as best estimate for ready-mixed concrete = 0.108 GJ/m^3
- Precast concrete: from PCA LCI of Portland concrete.
- Check: Vold & Rønning (1995): Energy for concrete production = 0.051 GJ/m^3 (similar to brick/block production in this case).

(d) Fuel

Approximately **2.2 MMTOE** was used for energy consumption at the concrete plant and **1.0 MMTOE** for transportation of mixed ready-mix concrete and concrete products to job sites. In total, **3.1 MMTOE** was used for the off-site mixing/prefabrication of concrete. The different types of energy sources can be seen in Figure 5.10.

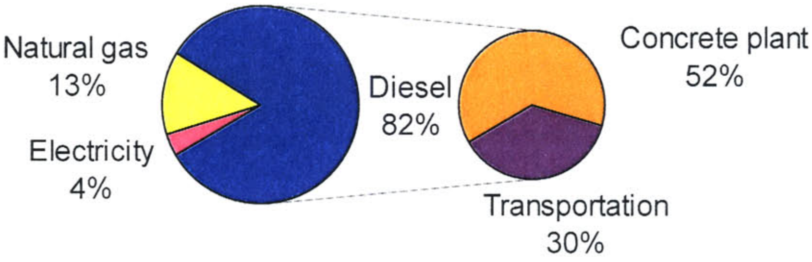


Figure 5.10 Fuel mix of off-site concrete plants by fuel type

- *Based on average PCA LCI of Portland concrete fuel type for concrete plant operations (see Appendix C: Table C3).*
- *Diesel represents the total transportation energy, i.e. 30% of the total energy used in this stage is for transportation.*

(e) Emissions

Approximately **25 Mt CO_2** was produced in total, with **20% or 5.2 Mt from concrete plants** and **80% or 20 Mt from transportation** of ready-mixed concrete and finished concrete products to the job site. Emissions from transportation are surprising high since only 30% of fuel was used for transportation. One reason is the differences in fuel mix: 100% of the fuel mix for transportation is diesel compared to 75% for concrete plant operations.

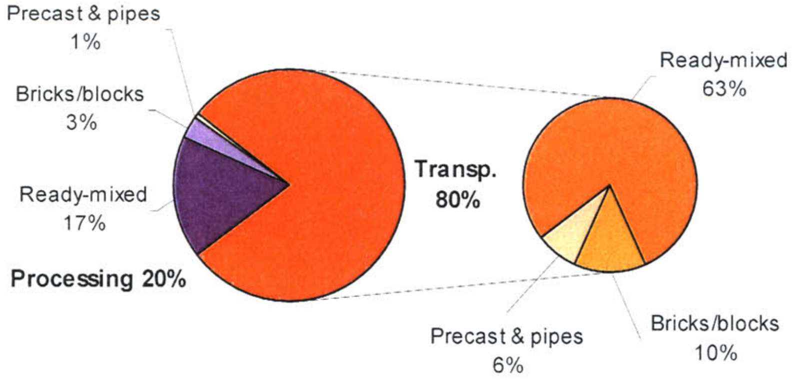
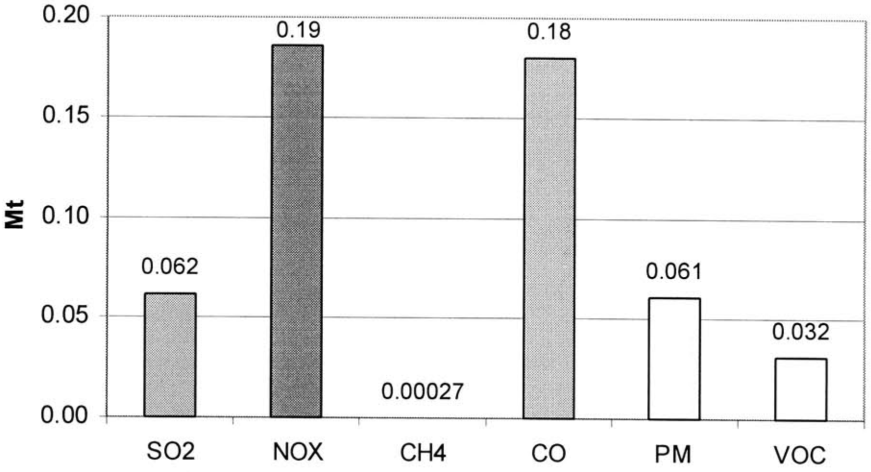


Figure 5.11 Total CO_2 emissions from 'Off-site production of concrete' stage



Includes emissions from processing and transportation.

Figure 5.12 Total emissions from 'Off-site production of concrete' stage

Notes:

- Computed using values from modified PCA LCI of Portland concrete emissions data (which is estimated from EPA AP-42 reports).
- CH_4 emissions data not available for ready-mixed, precast and pipes for the processing stage.
- For emissions for processing and transportation, see Appendix C: Table C4 and Table C5).
- For emissions factors, see Appendix C: Table C6 and Table C7).

5.4 Preliminary conclusions

1. More than three-quarters of the hydraulic cement was sent to off-site concrete plants to produce 780 Mt of ready-mixed concrete (67% of total consumed) and concrete products (11%).
2. In general, recycling rates of solid waste are high in the off-site concrete production process (estimated to be at least 90%).
3. Wastewater made up 25% of the total waste *generated* and 78% of the total waste *disposed*.
4. Precast concrete production produces 1/6th solid waste and wastewater compared to ready-mixed concrete on a per volume basis.
5. Road mix uses 2.5 times more water than general mix on a per volume basis.
6. Concrete blocks are almost twice as energy-intensive per unit volume compared to ready-mixed concrete, precast concrete and concrete pipes.

This chapter presented the production of concrete in off-site plants. The following chapter discusses the two main source activities carried out at the job site: on-site production and the use of concrete in buildings, highways and roads and other infrastructure.

CHAPTER 6 USE OF CONCRETE

6.1 Introduction

This chapter explores the physical aspect of using concrete during new construction, renovation and repair of the infrastructure on the job-site. In addition, the quantitative aspect of allocating concrete among the end-use categories is presented. The MFA results and details for each aspect are presented in Chapter 6.3.2 and Chapter 6.3.3 respectively. There are three types of general application processes occurring on the job site in the physical placement of concrete, as follows:

(i) On-site production	- small-scale projects carried out by homeowners (e.g. patchwork, mail box posts, driveways, walks, patios and garage floors.) - large-scale infrastructure projects where (a) ready-mix concrete plants are remote, (b) required aggregate size is too large for using ready-mixed concrete, and (c) required concrete could not be adequately supplied by an offsite plant (Army Corp of Engineers, 1994).
(ii) Placing of ready-mixed concrete	- as structural elements (e.g. beams, columns, walls, foundations) - as highway and road paving
(iii) Assembling of concrete products	- as construction systems (e.g. walls using concrete bricks/blocks)

In addition, the allocation of concrete for new construction and renovation and repair has three tiers of analysis with increasing specificity (by end-use categories, by construction process and by product). In this study, the three main end-use categories are buildings, highways and roads and other infrastructure. Allocation of waste concrete for demolition will be discussed in the next chapter.

6.2 Use of concrete

(i) On-site production of concrete

Concrete raw materials (cement, SCMs and aggregates) are directly transported from the cement plant, power plant and the quarry to the job site. Next, they are batched and mixed in-situ to be poured for direct use. This applies for building materials, mortar and other infrastructure (e.g. oil and gas wells and waste/water facilities). Cement used as building materials is generally for home use. Building material dealers (e.g. Home Depot and Lowes) sell them either in 94-lb bags of Portland cement or in premix concrete mix (including sand and gravel, which the customer will add water to and mix).[28]

(ii) Placing of ready-mixed concrete

Once ready-mixed concrete truck mixers arrive at the job site, the concrete is poured into formwork (removable 'molds' made with wood or steel formwork) using buckets, pumps or cranes. Next, the concrete is compacted to minimize voids (air pockets), screeded to correct levels (removing excess concrete for a predetermined level), floated (to fill voids and to smooth surface) and cured. Since adequate quantities have to be ordered from batch vendors to reduce lead times, excess orders might be returned to the batch vendors. If the excess is not returned, it forms part of the solid waste, along with leftover concrete from placing of concrete. Concrete sludge (while still wet) could be separated from wash water to reuse the coarse and fine aggregates for concrete production. If dried, the waste concrete is generally disposed of on-site or in landfills.

(iii) Assembly of concrete products

Concrete blocks, precast concrete and pipes are assembled on the job site with additional mortar or sealants.

6.3 MFA results

6.3.1 System boundaries

The processes included in the system boundaries are:

(xi) On-site production of concrete (mixing and placing)
  - as 'building materials'
  - as 'mortar'
  - as 'Other infrastructure'

(xii) Placing of ready-mixed concrete mixed in off-site concrete plants
  - as 'general construction'
  - as 'road construction'

(xiii) Assembly of concrete products

(xiv) Allocation of concrete by increasing degree of specificity:
  a) By end-use category: 'Buildings', 'Highways and roads' and 'Other infrastructure'
  b) By construction process: 'New construction' and 'Renovation and repair'
  c) By application process
    - on-site production of
      - 'building materials'
      - 'mortar'
      - 'other infrastructure'
    - placing of 'ready-mixed concrete'
      - as general mix
      - as road mix
    - assembly of 'concrete products'

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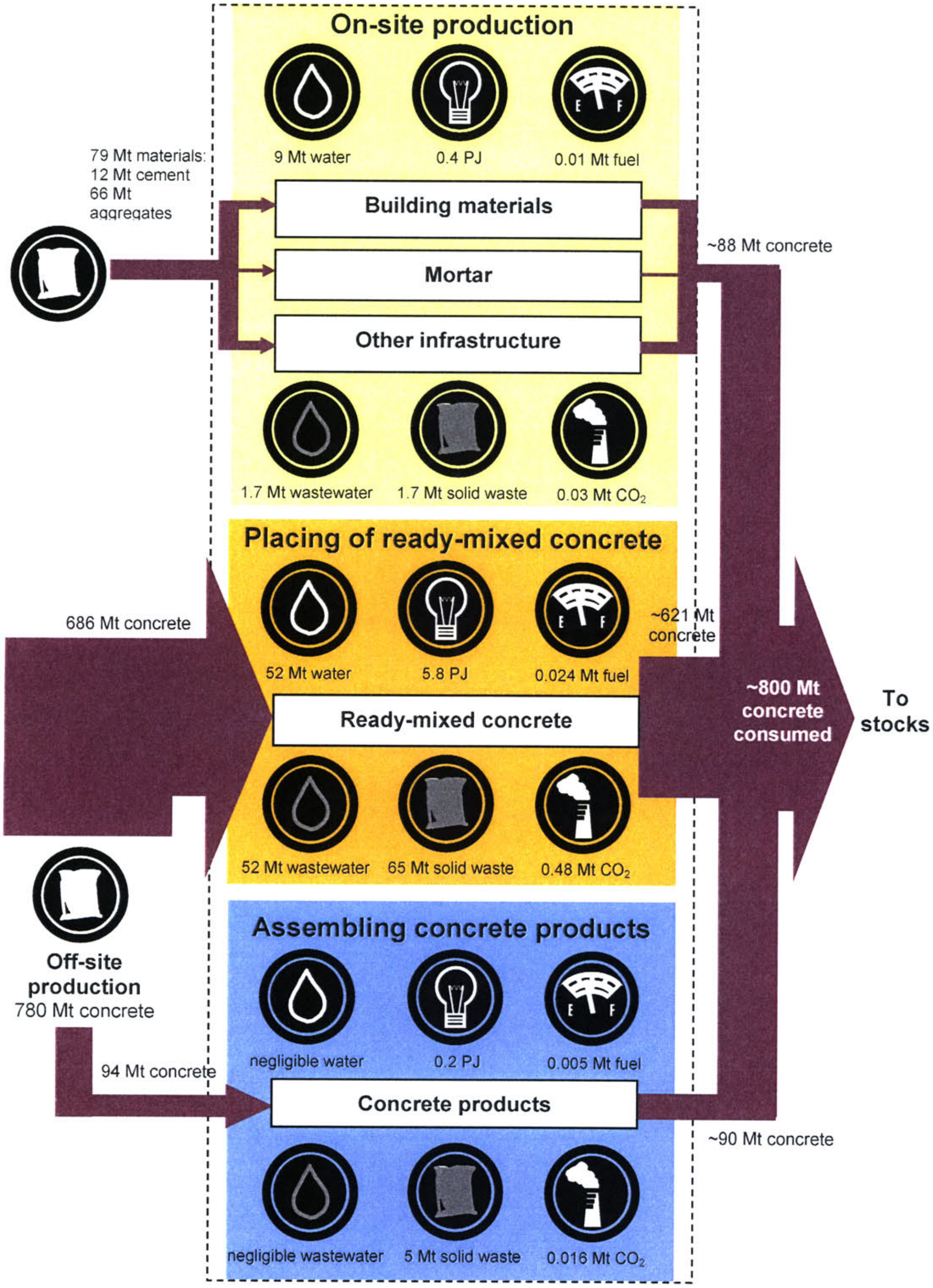
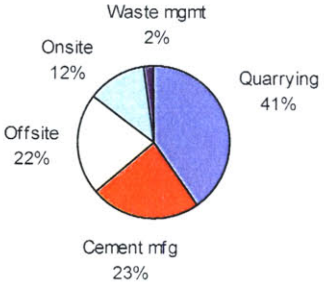
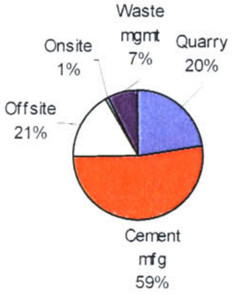
[28] Personal communication with Hendrik van Oss, USGS. April 2005.

6.3.2 Use of concrete

6.3.2.1 MFA of 'Use of concrete'



6.3.2.2 Summary

	Input	Output
Materials	**79 Mt** solid materials (includes 0.6% recycled materials) ≡ **790 Empire state buildings** & **780 Mt** concrete = 7,800 Empire state buildings **Total = 859 Mt solid materials** *[Total material throughput (including water) = 924 Mt]*	**800 Mt** concrete (353 mill m^3) added to stock = 8,000 Empire state buildings **71 Mt** waste concrete = 710 Empire state buildings **Total = 871 Mt usable and waste concrete**
Water	**61 Mt** water ≡ annual water consumption of **880,000 people** (population of San Jose, CA today) 	**54 Mt** effluent
Energy	**6.5 PJ** or **0.018 GJ/m^3 concrete** ≡ annual energy consumption of **160,000 people**  Piechart is similar for fuel and CO_2 emissions.	
Fuel	**0.2 MMTOE** ≡ annual fuel consumption of **140,000 automobiles**	
Emissions	-	**0.5 Mt CO_2** ≡ annual CO_2 emissions of **10,000 automobiles**

6.3.2.3 Details of MEFA

(a) Materials

The use of concrete for new construction, renovation and repair covers three subprocesses. (i) The on-site production of concrete produces building materials; mortar; and other infrastructure concrete (see Figure 6.1). (ii) The placing of ready-mixed concrete produces concrete for general and road construction (see Figure 6.2). 'General construction' refers to non-road construction and includes building and other infrastructure construction. (iii) The assembly of concrete products is shown in Figure 6.3.

To determine the mass flow outputs, the total solid waste produced is back-calculated from Chapter 7 (see Table 6.2). Next, estimations of solid waste produced from (i) on-site production and (iii) assembly of concrete products are computed using available coefficients and assumptions. These two estimates are subtracted from the total solid waste to derive the solid waste produced from (ii) placing of ready-mixed concrete, which is further allocated among the concrete types by a mass balance As a result, it is estimated that during general construction, **6%** of the ready-mixed concrete was disposed as waste. As for road construction, **18%** was disposed. Wastage from pouring of ready-mixed concrete in new construction, and renovation and repair projects is slightly low compared to a typical 10-20% range of solid waste generation (relative to the total weight of building materials bought to site[29]) (Cheung et al, 1993 cited in Poon et al, 2001). On the other hand, the wastage from road paving falls within the typical range.

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[29] Author assumes that the results of the study conducted in Hong Kong, applies to the United States. The results are also assumed to be valid for road and other infrastructure construction.

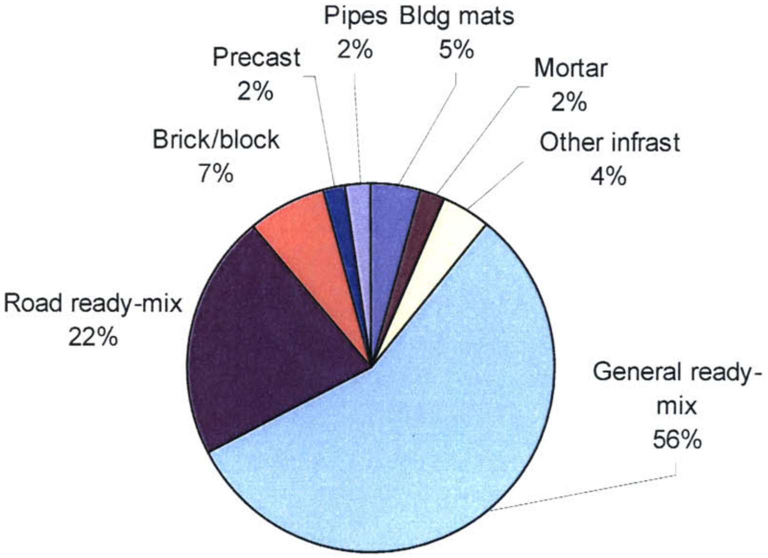


Figure 6.1 Distribution of 'Use of concrete' by concrete type (by percentages)

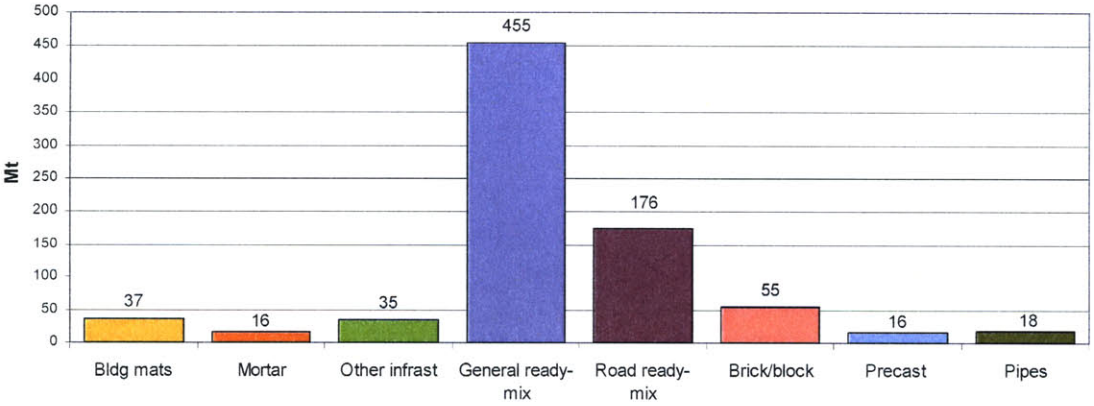


Figure 6.2 Distribution of 'Use of concrete' by concrete type (in values)

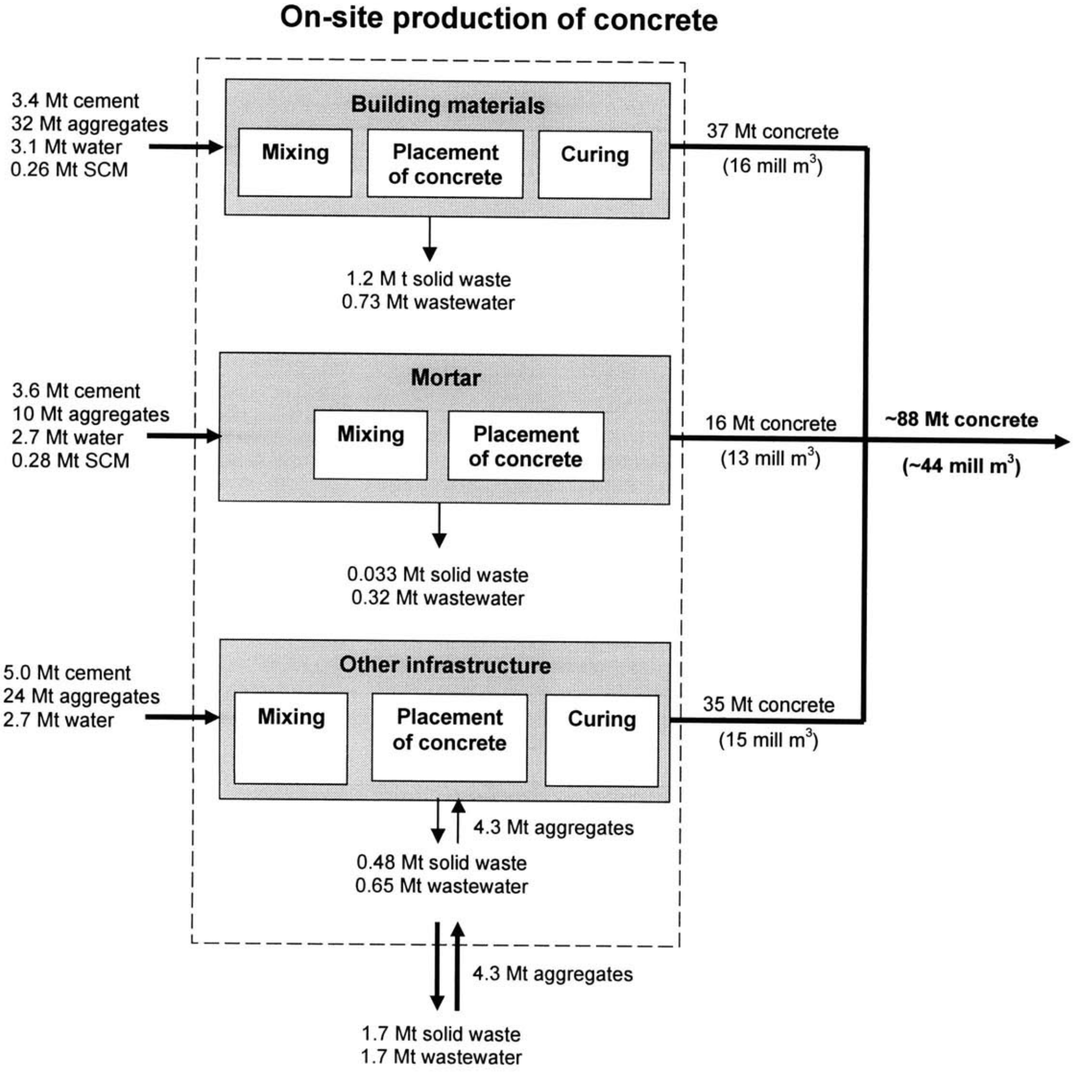


Figure 6.3 Detailed MFA of 'On-site production of concrete' stage

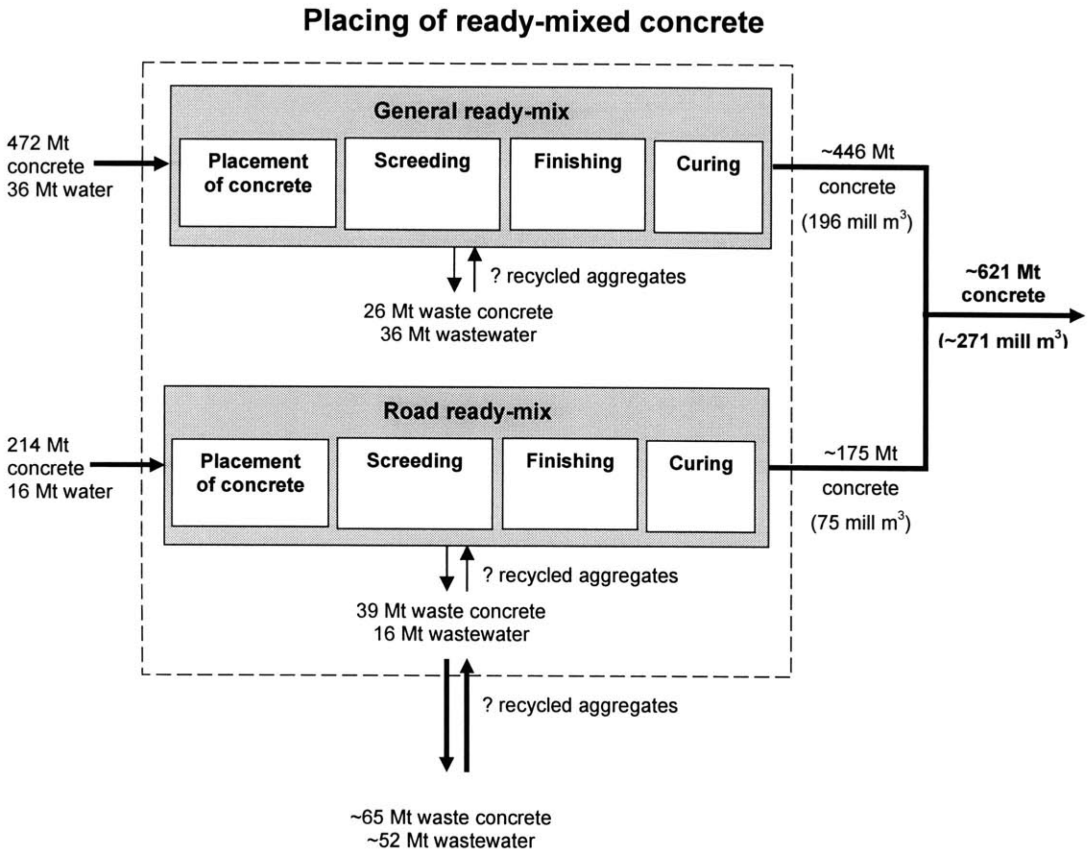
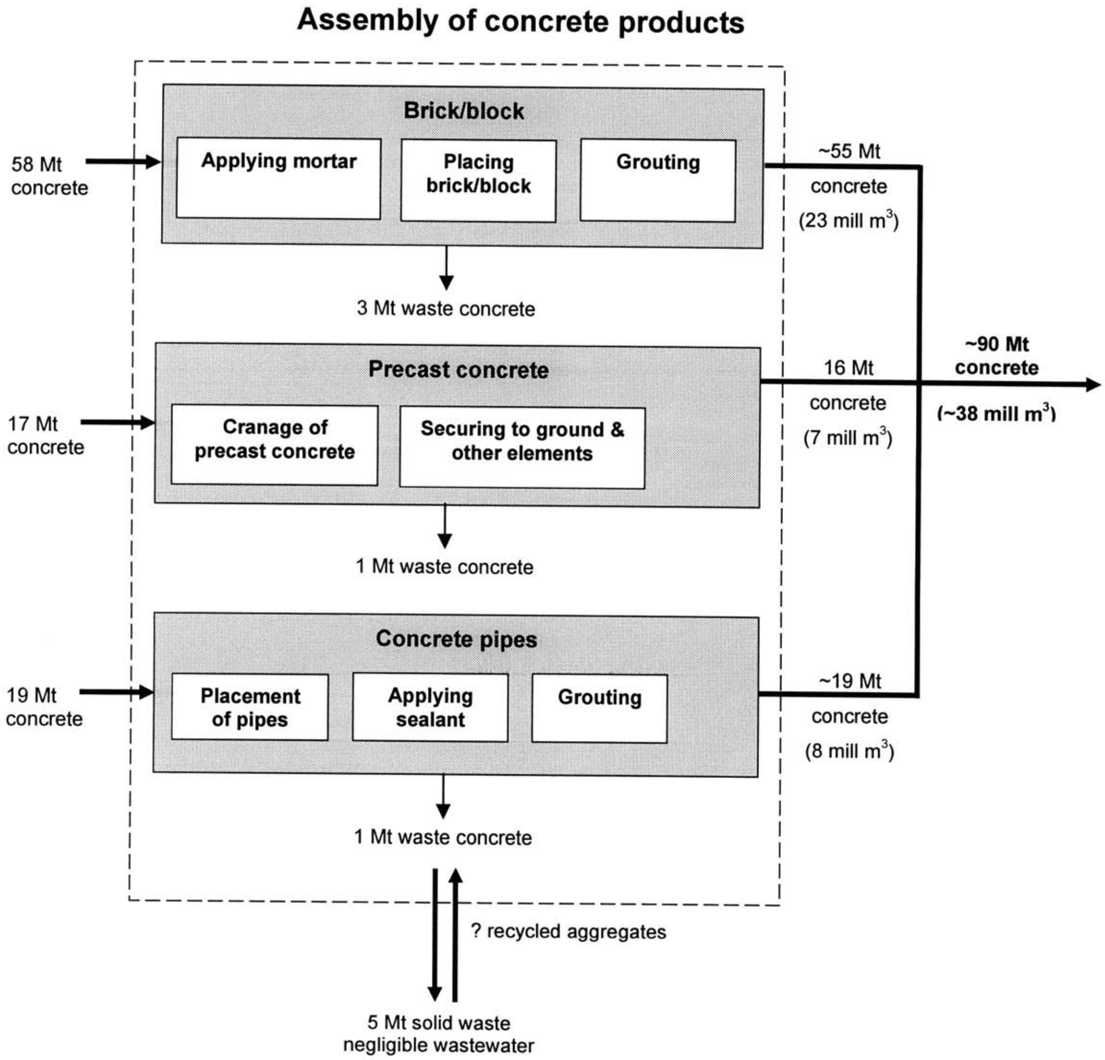


Figure 6.4 Detailed MFA of 'Placing of ready-mixed concrete' stage



- Process water and waste water produced assumed negligible; 5% wastage assumed.

Figure 6.5 Detailed MFA of 'Assembly of concrete products' stage

Table 6.1 Materials mass balance for 'Use of concrete'

	Total (Mt)	On-site production			Placing ready-mixed concrete		Assembling
		Building materials (Mt)	Mortar (Mt)	Other infrast. (Mt)	General mix	Road mix	Concrete products
Inputs							
Cement	**~12**	3.4	3.6	5.0	-	-	-
Aggregates	**~66**	32	10	24*	-	-	-
Total water	**~61**	8.6			52		-
- Mix water	~7	2.4	2.4	2.1	-	-	-
- Process water	~54	0.73	0.32	0.65	36	16	negligible
- Subtotal water		3.1	2.7	2.7	36	16	-
SCMs (Supplementary cementitious materials)	**~0.5**	0.26	0.28	-	-	-	-
Recycled waste as aggregates	**>~4**	-	-	4.3	?	?	?
Concrete	**~780**				472	214	94
Materials consumed in concrete**	**~90**	**~38**	**~16**	**~35**	**-**	**-**	**-**
Total inputs (on-site production)	**~91**	**~39**	**~16**	**~36**	**-**		
Total inputs (placing of ready-mixed concrete)	**~832**	**-**			**~508**	**~230**	**~94**
Total inputs	**~924**	**-**					
Outputs							
Concrete produced	**~88**	**~37**	**~16**	**~35**	**-**		
Net addition to stock	**~800**	**~37**	**~16**	**~35**	**~446**	**~175**	**~90**
Total waste	**~125**	2.0	0.33	1.1	~62	~55	~4.7
- Solids/waste concrete	~71	1.2	0.033	0.48	~26	~39	~4.7
- Wastewater	~54	0.73	0.32	0.65	~36	~16	negligible
Total outputs (on-site production)	**~91**	**~39**	**~16**	**~36**	**-**		
Total outputs (placing of ready-mixed concrete)	**~832**	**-**			**~508**	**~230**	**~94**
Total outputs	**~924**	**-**					

Only materials in system boundary included.

(Source: Author's calculations using 1996 USGS Cement MYB and MCS, PCA LCI of Portland concrete, ATHENA, Jeuffroy et al 1996)

*: Net of aggregates from recycled waste

**: Includes cement, aggregates (virgin/extracted and waste), mix water and SCM.

- Totals do not add up due to independent rounding.
- Assuming that all recycled material is used as aggregates.

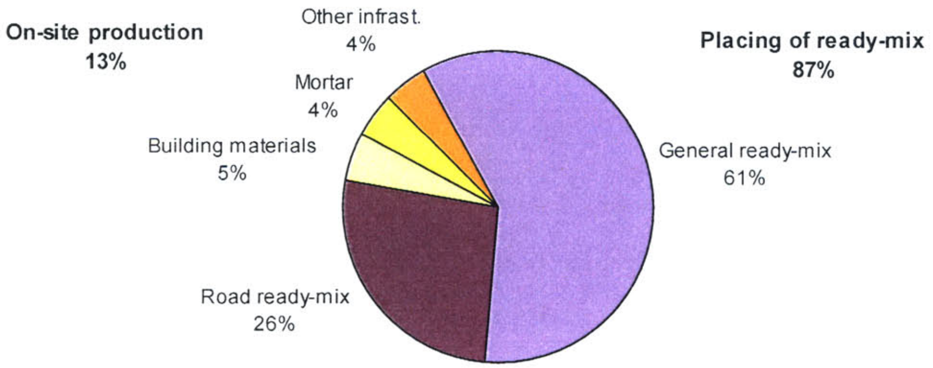
Table 6.2 Total solid waste for 'Use of concrete' stage

Solid waste (Mt)	Building materials	Mortar	Other infrast.	Ready-mixed concrete		Concrete products
				General	Road	
Returned concrete	-	-	3.8 (80%)	-	-	-
Mixer washout	-	-	0.14 (3%)	-	-	-
Equipment washout	-	-	0.82 (17%)	-	-	-
Total waste generated	**1.2**	**0.033**	**4.8**	**>26**	**>39**	**>5**
Waste recycled	-	-	**4.3 (90%)**	**?**	**?**	**?**
Waste disposed	**1.2**	**0.033**	**0.48**	**~26**	**~39**	**~4.7**

- *All the coefficients used are estimated from PCA LCI of Portland Concrete and ATHENA or based on author's assumptions* (see Appendix D: Table D 1).

(b) Water

In total, approximately **54 Mt of water** was used. The quantity of mix water used is **7 Mt or 13%** for cement hydration. Process water accounted for the remaining **47 Mt or 87%** for washing of mixers, forms and tools in general and sawing of concrete roads and exposing aggregates, etc. Road paving consumed almost half of the total water used. The recycling rate is not known but might be close to 70% if all the wash water is recycled. Water used for placing ready-mixed concrete is estimated to be similar to concrete plant operations, since it is pretty close to the process water used in road paving. More information would be required to determine the quantity of and recycling of water used in placing ready-mixed concrete. Water used during the assembly of concrete products is assumed to be negligible.



- *Includes mix water and process water.*

Figure 6.6 Total water input of 'Use of concrete' stage by concrete type

Table 6.3 Total water consumption for 'Use of concrete' stage by concrete type

Type	Input			Output			
	Mix water (Mt)	Process water* (Mt)	Total influent (Mt)	Equipment wash out (Mt)	Miscellaneous (Mt)	Total effluent (Mt)	Embodied water (Mt)
On-site production of concrete							
Building materials	2.4	0.73	3.1	0.25	0.48	0.73	2.4
Mortar	2.4	0.32	2.7	0.32		0.3	2.4
Other infrastructure	2.1	0.65	2.7	0.22	0.43	0.65	2.1
Subtotal	*6.9*	*1.7*	*8.5*	*1.7*		*1.7*	*6.9*
Placing of ready-mixed concrete							
General	-	36	36	36		36	-
Highways and roads	-	16	16	16		16	-
Subtotal	-	*52*	*52*	*52*		*52*	-
Total	***6.9***	***54***	***54***	***54***		***54***	***6.9***

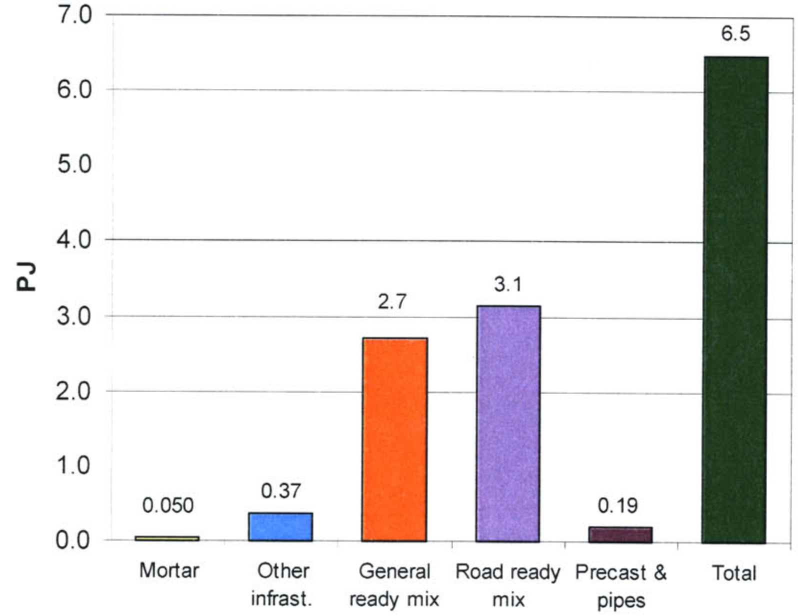
'Mix water' = concrete mix water, 'Process water' = water for washing pumps, cranes, forms and tools, sawing, exposing aggregate surface and washing of concrete roads, *'Embodied water' = water used for cement hydration to form cement binder for concrete.*

*: Process water is the average of PCA LCI of Portland Concrete and ATHENA coefficients.

- For coefficients, see Appendix D: Table D2.

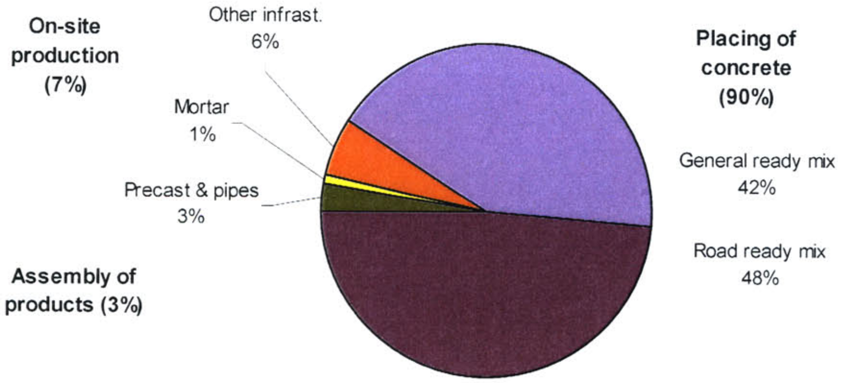
(c) Energy

An estimated total of **6.5 PJ** was used. Similarly, road paving was relatively more resource-intensive per unit mass. It consumed as much as 48% of the total energy used for using concrete on the job site (see Figure 6.7 and Figure 6.8).



- Energy for production of building materials assumed negligible.

Figure 6.7 Energy consumption of 'Use of concrete' stage (by values)



- Includes mixing and placing energy.

Figure 6.8 Energy consumption of 'Use of concrete' stage (in percentages)

Table 6.4 Total energy consumption for 'Use of concrete'

	Batching energy (PJ)	**Placing energy (PJ)**	**Total energy (PJ)**
On-site production			
Building materials	negligible	negligible	negligible
Mortar	0.050	negligible	0.050
Other infrastructure	0.18	0.19	0.37
Subtotal	*0.23*	*0.19*	***0.42***
Placing of ready-mixed concrete			
General (mix)	n/a	2.7	2.7
Highways & roads	n/a	3.1	3.1
Subtotal	*n/a*	*5.9*	***5.9***
Assembly of concrete products			
Brick/block	negligible	negligible	negligible
Precast	n/a	0.088	0.088
Pipes	n/a	0.10	0.10
Subtotal	*n/a*	0.19	**0.19**
Total	**0.23**	**6.2**	**6.5**

- For coefficients, see Table 6.5.

Table 6.5 Energy coefficients for 'Use of concrete' stage

	Batching (GJ/m^3 concrete)	**Placing (GJ/m^3 concrete)**
On-site production		
Building materials	negligible[a]	negligible[a]
Mortar	0.00395[b]	negligible[c]
Other infrastructure	0.012[d]	0.013[d]
Placing of ready-mixed concrete		
Ready-mixed (general)	n/a	0.013[d]
Highways & roads (paving)	n/a	0.034[e]
Assembly of concrete products		
Brick/block	negligible	negligible
Precast	n/a	0.013[d]
Pipes	n/a	0.013[d]

(Source: ATHENA, 1999, Brocklesby & Davison, 2000, Zapata & Gambatese, 2005)

[a]: Author assumes energy used for batching and placing concrete for use as building materials are negligible with the assumption that most are done manually.

[b]: From ATHENA

[c]: Author's assumption.

[d] From Brocklesby & Davison (2000): Author assumes batching energy for 'Other infrastructure' is similar to averaged values (0.012 GJ/m^3 concrete) for on-site batching (0.006 GJ/m^3 concrete) and static batching (0.018 GJ/m^3 concrete). Placing energy is assumed the average of energy used for cranes (0.013 GJ/m^3 concrete) and pumps (0.013 GJ/m^3 concrete).

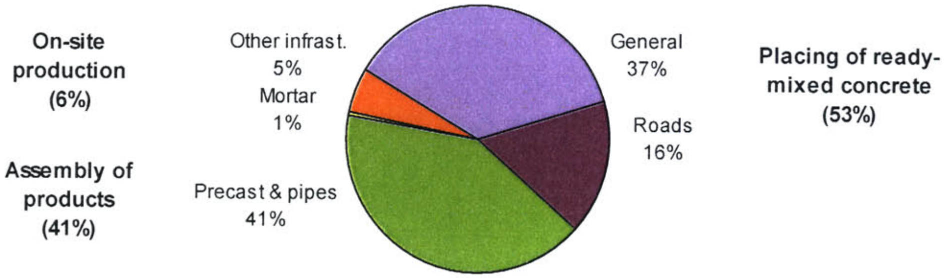
[e]: From Zapata & Gambatese (2005)

(d) Fuel

In terms of fuel, **0.16 MMTOE** was used. Most on-site batching, mixing and placing operations consume diesel fuel.

(e) Emissions

The relatively small amount of energy expended for this stage resulted in **0.52 Mt** of CO_2 emitted. The transportation energy of raw materials to the job-site for on-site production has been factored in as transportation and distribution energy in the extraction of raw materials stage[30] (see Chapter 3).



- *Transportation energy included in 'Extraction of raw materials' stage*

Figure 6.9 Total CO_2 emissions from 'Use of concrete' stage by concrete product

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[30] As an approximation, the energy expended and distance traveled for the transportation of raw materials to concrete plants are the same as transportation to the job-site directly. More specific studies would be required to find the average of the variable distances traveled and associated energy consumption.

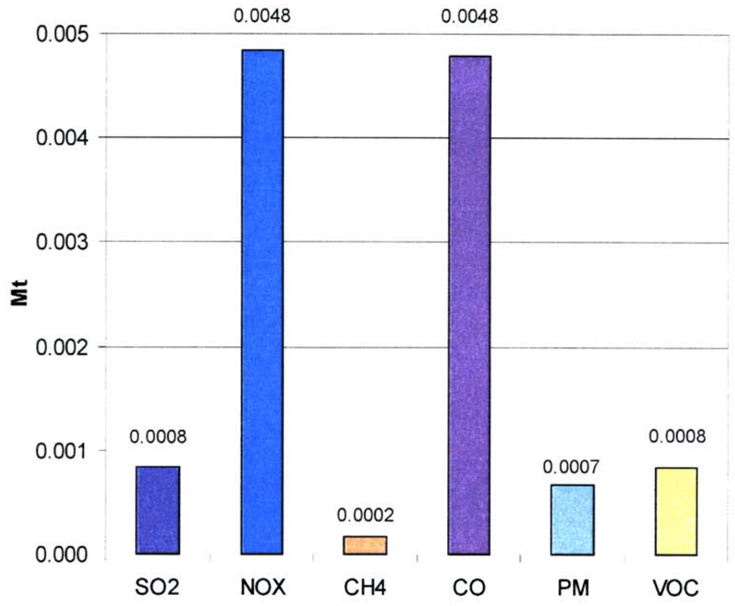


Figure 6.10 Total emissions from 'Use of concrete' stage

Notes:

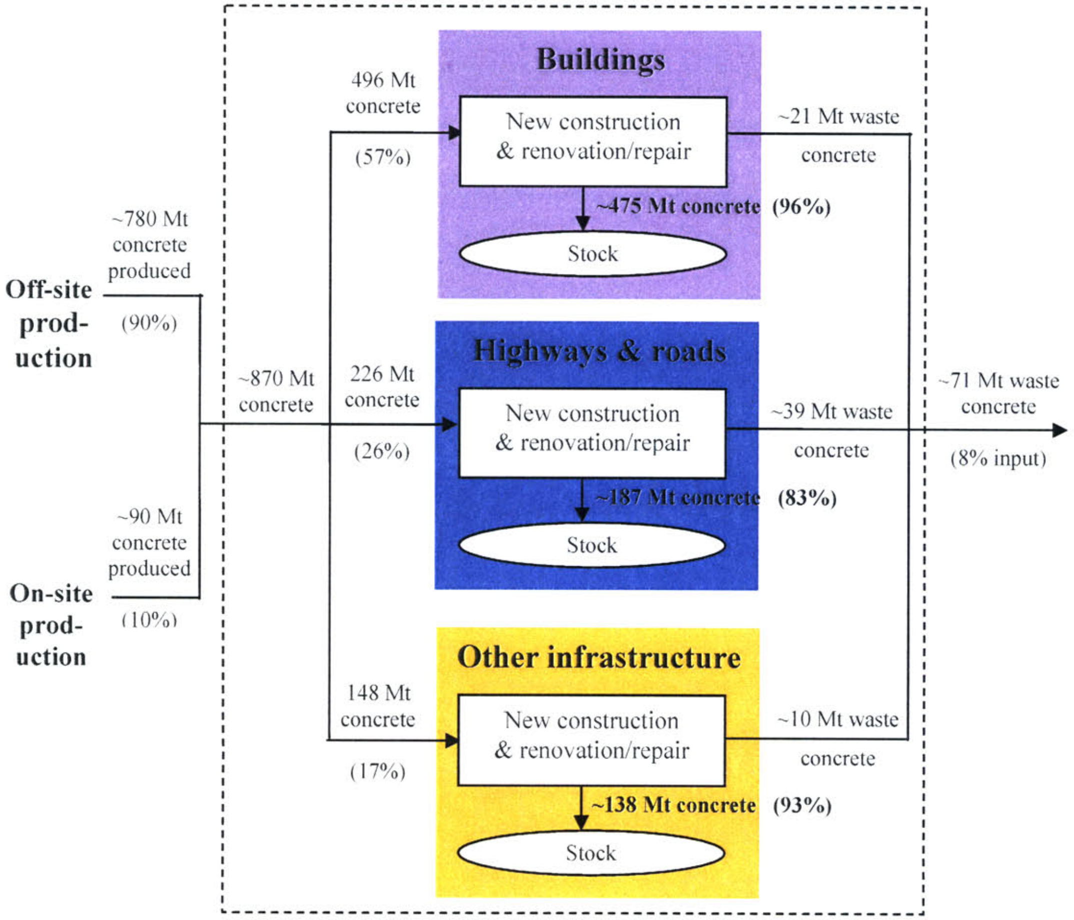
- Building materials emissions assumed negligible due to assumption of manual mixing and placing.
- Computed using values from modified PCA LCI of Portland concrete emissions data (which is estimated from EPA AP-42 reports).
- For emissions by sub-process (batching and placing), see Appendix D: Table D 3.
- For emissions factors, see Appendix D: Table D 4.

6.3.3 Allocation of concrete

This section looks at how concrete types are distributed among end-use categories, construction process and types of application. More importantly, it shows the magnitude of additions to stock in buildings, highways and roads and other infrastructure for a given year. This information could be used as part of the groundwork of a set of time-series data for trend analysis. As mentioned in the earlier section, the waste produced from the use of concrete is back-calculated and approximated from Chapter 7 using mass balances. It should also be noted that for simplification of calculations, point estimates were used instead of ranges.

The overview of the allocation of concrete among buildings, highways and roads and other infrastructure is shown in Figure 6.11. Figure 6.12 and Figure 6.13 show the allocation of concrete within buildings; highways, roads and other infrastructure in more details respectively. The system boundaries start from the initial use of concrete at the job-site during new construction, renovation and repair, i.e. the start of placing ready-mixed concrete, assembly of concrete products and mixing of on-site produced concrete in buildings; highways and roads; and other infrastructure. The system includes any additions of stock and ends to the point when waste concrete is produced. The disposal of waste concrete is covered in the next chapter.

6.3.3.1 MFA of 'Allocation of concrete' by end-use category



Off-site produced concrete: 90% ready-mixed concrete (68% general; 32% road); 10% concrete products
On-site produced concrete: 88% general concrete; 7% brick/block; 2% precast concrete; 2% concrete pipes

Figure 6.11 MFA of 'Allocation of concrete' by end-use category

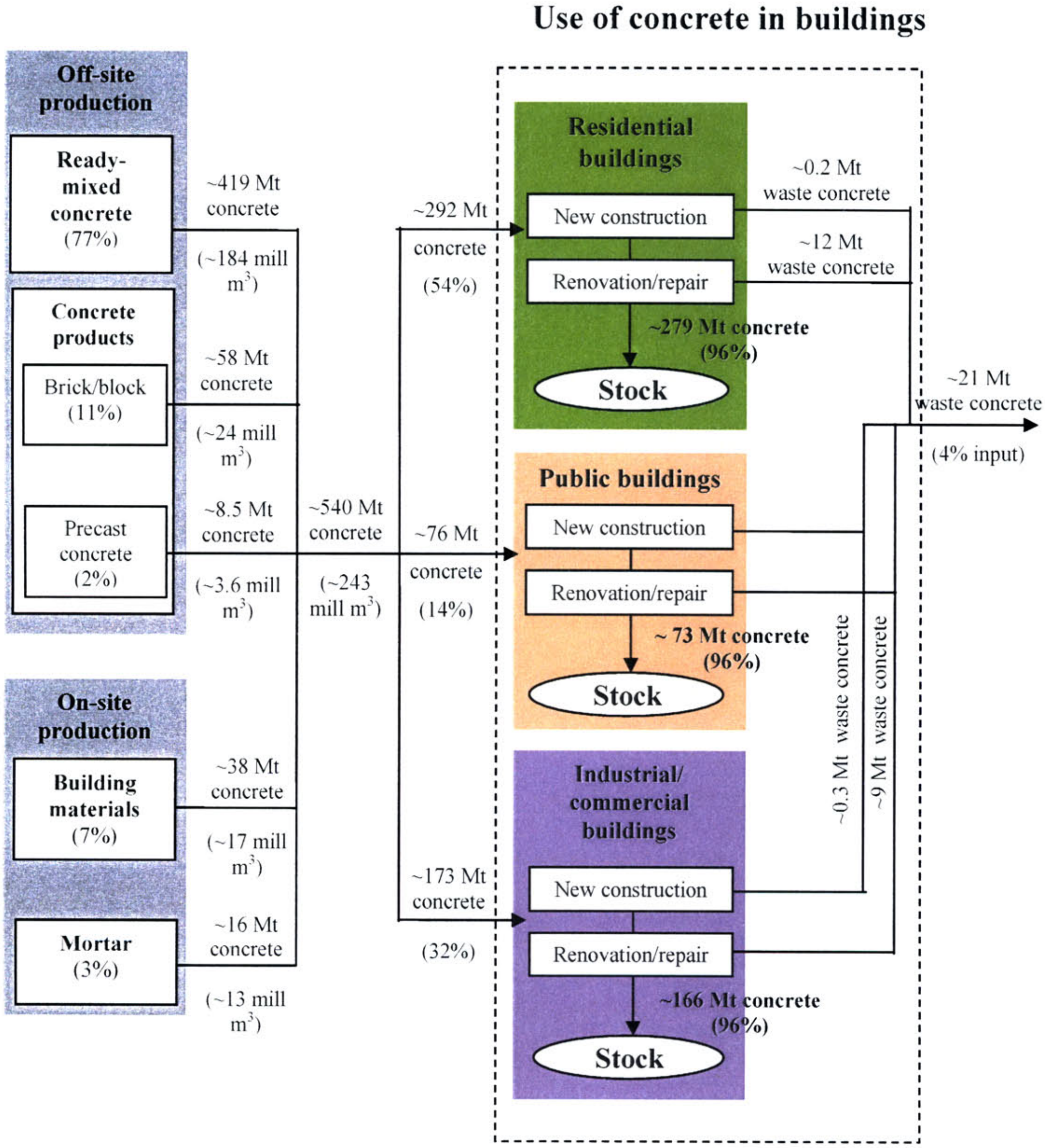


Figure 6.12 Detailed mass flow of concrete in 'Buildings'

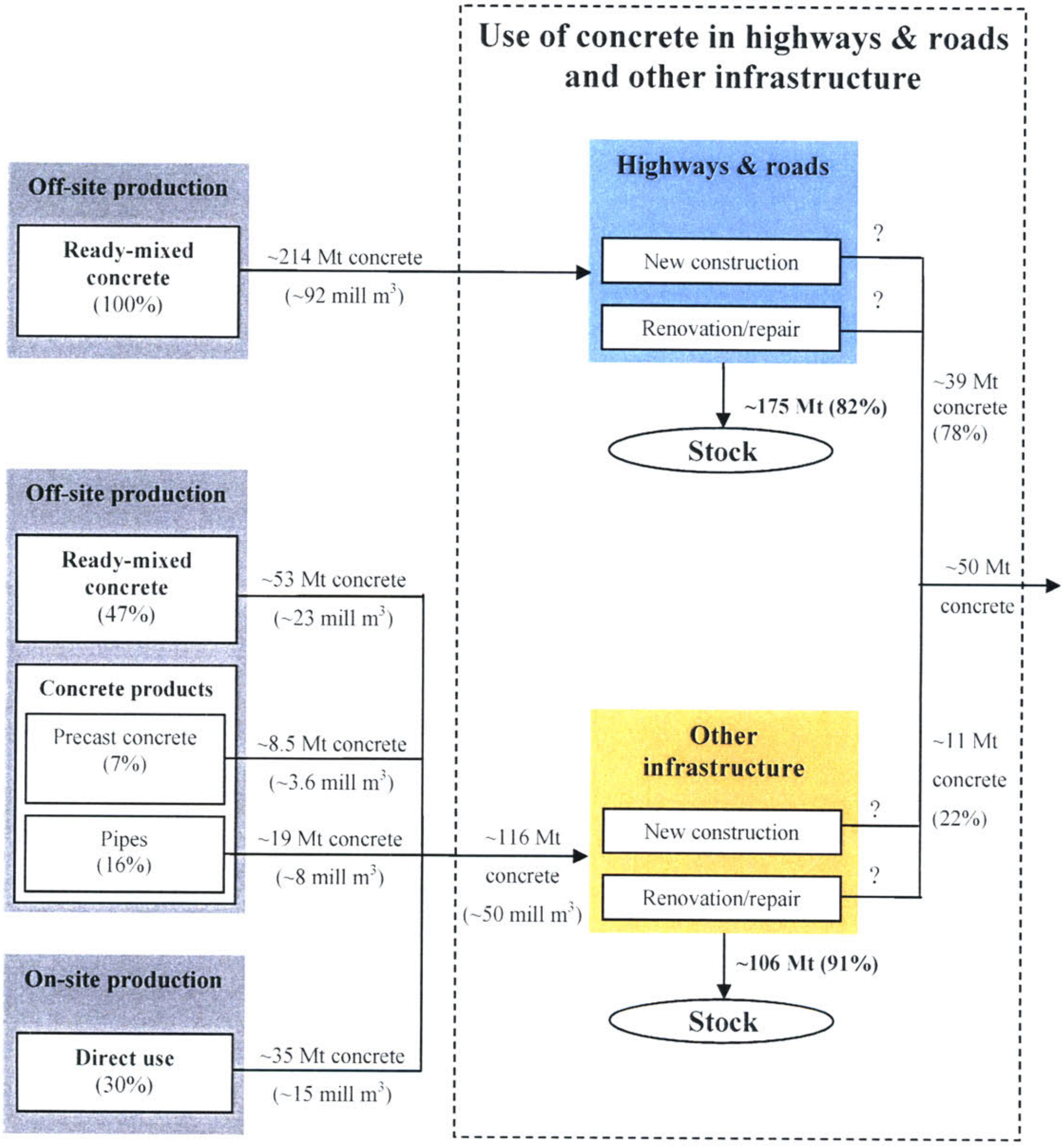


Figure 6.13 Detailed mass flow of concrete in 'Highways and roads' and 'Other infrastructure'

6.3.3.2 Summary

This section summarizes how concrete is used in the United States by end-use categories and by concrete types. The dominant use for concrete in 1996 was in buildings, followed by highways and other infrastructure (see Figure 6.14). A more in-depth examination is shown in Figure 6.15. The majority of concrete was used in residential buildings (31%.) Approximately 77% of the concrete used in buildings was ready-mixed concrete and the second major concrete type is concrete blocks (see Figure 6.16). The study assumes that 100% of the concrete used in highways and roads are ready-mixed concrete based on the road mix designs used in the United States. Furthermore, it is postulated that on-site concrete production is nearly as favorable as ready-mixed concrete for use in other infrastructure. The additions to stock appear to be well-correlated with the quantity of concrete poured for the end-use category. Due to the large proportion of concrete used in buildings, the quantity of additions to the building stock was the greatest. In reality, the additions would be lower since the estimate of waste concrete generated from buildings appears to be low. Overall, it is approximated that **800 Mt of concrete is accumulated** in the physical infrastructure stock in the United States in 1996.

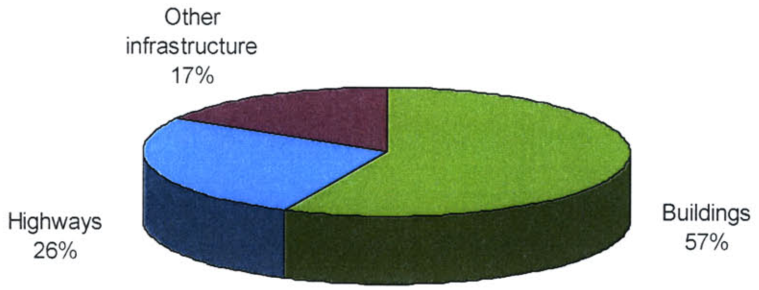


Figure 6.14 Allocation of concrete by end-use category
(For allocation by concrete type, see Figure 6.1)

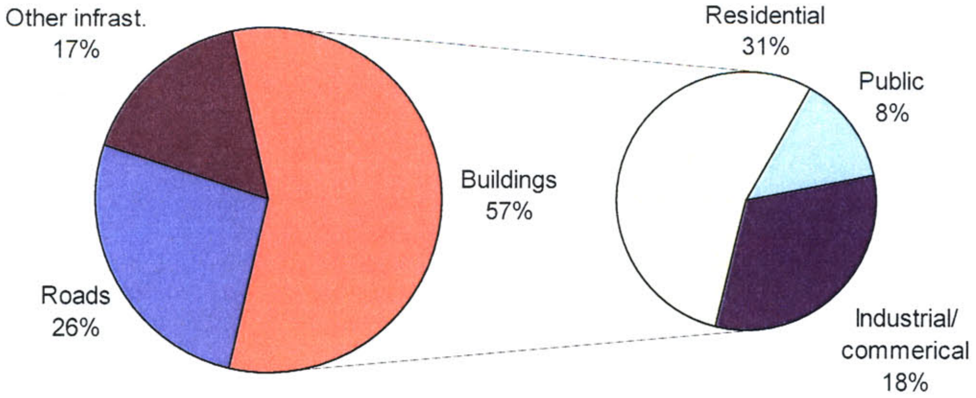


Figure 6.15 Allocation of concrete by end-use categories and by building types

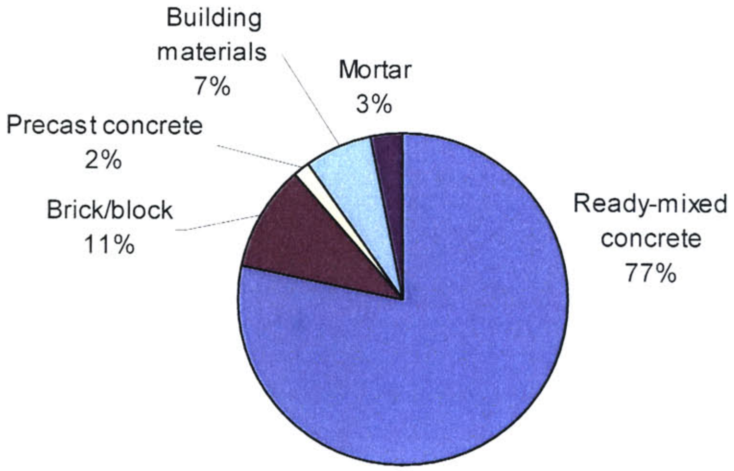


Figure 6.16 Allocation of concrete in 'Buildings' by concrete type

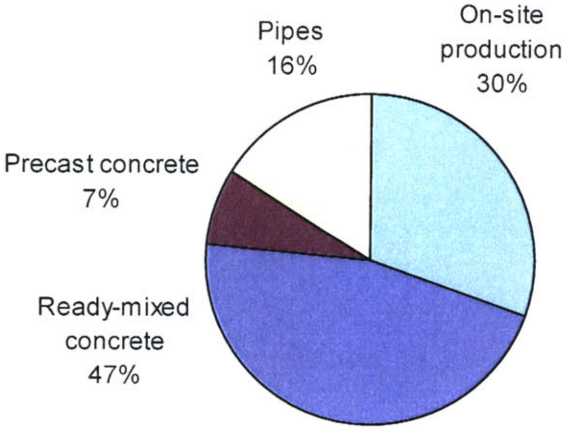


Figure 6.17 Allocation of concrete in 'Other infrastructure' by concrete type

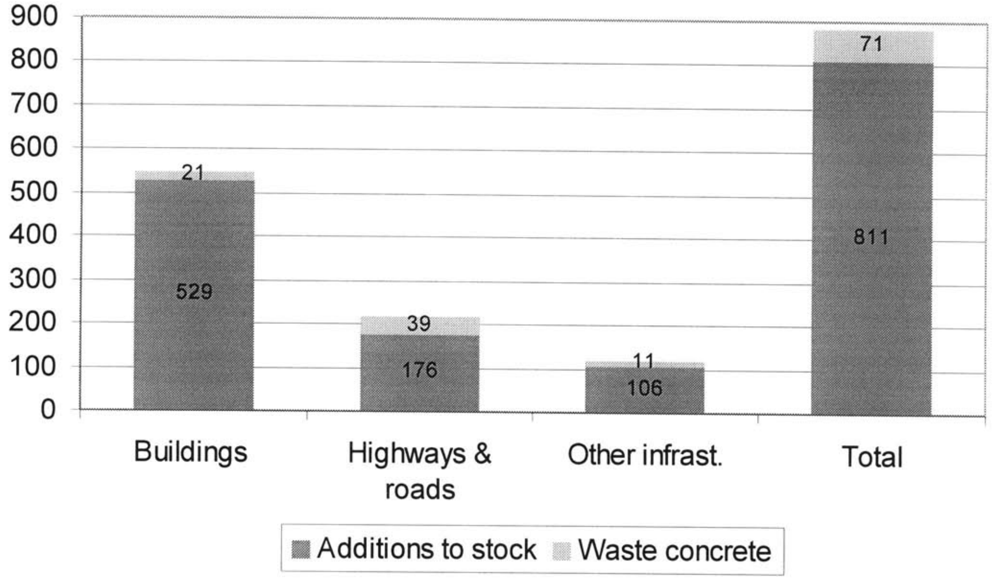


Figure 6.18 Additions to stock by end-use category

6.3.3.3 Details of MEFA

This section explains the three-tiered analysis of the allocation of concrete. First, the tracking of concrete flows is narrowed down by end-use category, i.e. buildings; highways and roads; and other infrastructure. Next, within the building end-use category, the flows are categorized by the type of buildings they flow into: residential; industrial and commercial; and public. The last tier analyzes the composition of concrete type within each end-use category as a combination of ready-mixed concrete, concrete products and on-site produced concrete.

Due to additions to stock, less mass flows out of the system boundary than flowing in. Some insights on the dynamics of additions to stock are made:

(i) It is estimated that the majority of the waste comes from highways and roads (55%), followed by buildings (30%) and other infrastructure (15%).

(ii) The building stock accumulates the fastest (96%), followed by other infrastructure (93%), then highways and roads (83%). In other words, it takes the road stock 45% longer to double compared to the building stock.

(iii) Inversely, the construction of roads is less material-efficient compared to buildings and other infrastructure. Road construction wastes three times more than buildings in total.

(i) Allocation by end-use category

The USGS and PCA Apparent Use of Portland Cement Summary are used, along with the author's assumptions. Since these are not sources of first-hand information, this three-tiered analysis should only serve as an approximation until more specific data is collected. The USGS provides the distribution of Portland cement by customer types,[31,32] specifically producers of ready-mixed concrete and concrete products, building materials dealers, contractors (largely for roads) and Government; while the Portland Cement Association (PCA) allocates Portland cement by end-use categories, such as buildings (residential, public and industrial/commercial), highways, streets and roads, public works, etc. Ambiguity is inherent in the data sets because they are derived from surveys. The 1996 USGS Cement MYB mentions an interpretation problem between the dualistic interpretations of "type of customer" and "type of use." For example, a cement plant would find it difficult to distinguish whether ready-mix cement used for road-paving by its customer belongs to the ready-mix or road-paving category. By iteration, the first and third tiers of the analysis are determined (see Table 6.7) by allocating the percentage distribution among the end-use categories from the PCA Apparent Use summaries[33] as supplemented by the concrete type distribution from the USGS Cement MYB.[34] The mass balance and volume balance are shown in Table 6.7 and Table 6.8.

Table 6.6 Percentage distribution by concrete type and end-use category

	Buildings (%)	**Highways & roads (%)**	**Other infrastructure (%)**	**Total %**
As ready mix	43.8	26.4	5.5	75.7
As concrete products	5.5	-	5.5	11.0
As building materials	3.8	-	-	3.8
As mortar	4.0	-	-	4.0
As other infrastructure directly	-	-	5.5	5.5
Total	**57.0**	**26.4**	**16.6**	**100**

(Source: Author's estimates based on USGS Cement MCS and MYB 1996 and PCA Apparent Use of Portland Cement Summary, 1998)

- PCA figures shown in last row.
- See Notes for Table 6.6 in Appendix D for iteration process.

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[31] The percentage distribution of sub-product types is only available for specified amounts. When necessary, the percentage distribution is weighed to account for unspecified amounts (a lump sum over which the distribution of sub-product types is unknown.)

[32] The total of 83.0 Mt in USGS MYB Table 14, which lists cement used by type of customer using surveys, does not add up to the apparent consumption of 90.4 Mt). Therefore, the percentage breakdown of data is used instead.

[33] See Appendix D Table D 5.

[34] See Appendix D Table D 6.

Table 6.7 Materials mass balance of 'Use of concrete' by end-use category

	Total (Mt)	Buildings (Mt)	Highways & roads (Mt)	Other infrast. (Mt)
Inputs				
Off-site produced	**~780**			
- Ready-mixed concrete	**~686**	~419	~214	~53
- General	~472	~419	-	~53
- Road	~214	-	~214	-
- Concrete products	**~94**	~67	-	~28
- Brick/block	~58	~58	-	-
- Precast concrete	~17	~8.5	-	~8.5
- Pipes	~19	-	-	~19
On-site produced	**~89**			
- Building materials	**~38**	~38	-	-
- Mortar	**~16**	~16	-	-
- Other infrastructure concrete	**~35**	-	-	~35
Total inputs	**~870**	~540	~214	~116
Outputs				
Additions to stock	**~800**	~519	~176	~106
Total waste*	**~71**	~21	~39	~11
Total outputs	**~870**	~540	~215	~116

(Source: Author's calculations using 1996 USGS Cement MYB and MCS, 1998 PCA Apparent Use Summary, 1998 EPA 'Characterization of Building-related Construction and Demolition Waste' report)

* *From new construction & renovation/repair.*

- May not add up to total due to independent rounding.

Table 6.8 Materials volume balance of 'Use of concrete' by structure

	Total (mill m^3)	Buildings (mill m^3)	Highways & roads (mill m^3)	Other infrast. (mill m^3)
Inputs				
Off-site produced	**~339**			
- Ready-mixed concrete	**~299**	~184	~92	~23
- General	~207	~184	-	~23
- Road	~92	-	~92	-
- Concrete products	**~40**	~28	-	~12
- Brick/block	~24	~24	-	-
- Precast concrete	~7	~3.6	-	~3.6
- Pipes	~8	-	-	~8
On-site produced	**~44**			
- Building materials	**~17**	~17	-	-
- Mortar	**~13**	~13	-	-
- Other infrastructure	**~15**	-	-	~15
Total inputs	**~383**	~242	~92	~50
Outputs				
Additions to stock	**~352**	~227	~76	~46
Total waste*	**~31**	~9.3	~16	~4
Total outputs	**~383**	~243	~92	~50

(Source: Author's calculations based on Table 6.7 using assumed design mix of each concrete type.)

* *For new construction & renovation/repair (from on-site and off-site produced concrete).*

- May not add up to total due to independent rounding.

(ii) Allocation by building type

The 1998 and 1999 PCA apparent use of Portland cement summaries are used since the summaries are not available for 1996. The 2000 and 2003 apparent use information on the PCA website are also used as a check. No significant deviations in the apparent use for 1998 – 2003 are noted (see Appendix D: Table D 14).[35] Therefore, a fair assumption is made that the 1996 apparent use percentage breakdown is similar to that of 1998 and 1999 (see Table 6.9).

Table 6.9 Percent breakdown of concrete use by building type

Residential buildings	Public buildings	Industrial and commercial buildings	Total
54.4%	14.0%	31.6%	100%

(iii) Allocation by concrete mix

To account for the diversity of concrete types used in the United States, the allocation of concrete by concrete mix is distinguished. This will allow for more accurate accounting of raw materials, water use, energy use and environmental impacts.

Table 6.10 Estimated breakdown of cement use by type of concrete mix

Type of production	Concrete type	Concrete product	%	Mass of cement (Mt)	Mass of concrete* (Mt)	Volume of concrete* (mill m^3)
Off-site production	Ready-mixed concrete	20 MPa	44	40	447	195
		30 MPa	1.5	1.3	12	5.2
		35 MPa	3.5	3.1	22	9.3
		Road mix	26	24	35	93
		Subtotal	**76**	**68**	**696**	**302**
	Concrete products	Brick/block	5.2	4.7	58	24
		50 MPa precast	1.2	1.0	4.9	2.1
		70 MPa precast	1.2	1.0	5.5	2.4
		Arch. precast	1.2	1.0	6.5	2.7
		Pipes	2.3	2.1	19	8.1
		Subtotal	**11**	**10**	**94**	**40**
On-site production	**Bldg mats**		3.8	3.4	38	17
	Mortar		4.0	3.6	16	13
	Other infrastructure		5.5	5.0	35	15
Total			**100**	**90**	**881**	**386**

* Estimated amounts of concrete produced –wastages during concrete production not accounted for.

- See Notes for Table 6.10 in Appendix D for assumptions and concrete mix design for each concrete type.

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[35] The only change occurred at around 2000. There was a 20% diversion from residential buildings to highways and a redistribution of cement from industrial and commercial buildings to residential buildings.

6.4 Preliminary conclusions

1. Over half of the concrete was used in buildings (57%), followed by highways (26%) and other infrastructure (17%).
2. Of the concrete used in buildings, approximately 54% of the concrete was used in residential buildings, and the remaining 32% in industrial/commercial buildings and 14% public buildings.
3. The top three concrete types are general ready-mixed concrete (56%), followed by road ready-mixed concrete (22%) and concrete block (7%).
4. On the job site, placing ready-mixed concrete uses the most energy and water compared to the on-site production of concrete and assembly of concrete products.
5. From the preliminary analysis, road paving is the major resource consumer. During the use of concrete stage, it consumes up to 50% of the total energy used and produces the most waste (55% of the total solid waste produced).
6. Though building construction generates the least amount of waste (at 4% of input concrete), it produces the second highest quantity of waste (30%) in total due to its sheer mass (54% of total mass of concrete produced).
7. The building stock accumulates the fastest (96%), followed by other infrastructure (93%), then highways and roads (83%). In other words, it takes the road stock 45% longer to double compared to the building stock.

Throughout the analysis, data uncertainty is evident for processes beyond concrete plant operations. One major data limitation of this study is the assumption that the transportation energy of raw materials to off-site concrete plants and directly to job sites is similar. Subsequently, it is difficult to assess the differences in energy consumption and emissions generated from off-site production versus on-site production. Another limitation of this study is the on-site solid waste production. Many assumptions are made and values are back calculated using mass balances. On-site solid waste production data or surveys can aid in improving the accuracy of determining additions to building stock.

This chapter presented (i) the physical aspect of how concrete was used, including the on-site production of concrete, the placing and assembly of off-site produced concrete. In addition, (ii) the allocation of concrete in buildings, highways, and roads and other infrastructure; and the corresponding concrete type composition are analyzed. The next chapter will present the waste management of concrete produced from the use of concrete in this stage (mainly construction and renovation waste) and from the demolition of physical infrastructures.

CHAPTER 7 WASTE MANAGEMENT OF CONCRETE

7.1 Introduction

Construction and demolition (C&D) waste is produced when building materials (such as wood, metal, bricks, shingles, dry wall, glass) and other materials (such as earth and trees) are removed during the (i) construction and renovation/repair and (ii) demolition from buildings, highways and roads and other infrastructure. It accounts for 23 – 33% of municipal solid waste (Environmental Council of Concrete Organizations, 1997 cited by Meyer, 2002). Waste concrete makes up 67% by weight (53% of the volume) of the demolition waste in North America (Science Council of British Columbia, 1991 cited by AIA ERG, 1996). Given that 20 – 30 times more demolition waste is produced than construction debris (Franklin/EPA, 1998), it is not surprising that waste concrete is the single largest component of C&D waste. Waste concrete is managed by recycling (50 – 60%) (EPA, 2003), or by disposal in landfills. In recent years, there has been a trend to create separate landfills for construction waste in order to relieve the burden of C&D waste on municipal landfills.

7.2 Waste management of concrete

The generation of waste concrete in the construction and renovation/repair process is described in Chapter 6. Waste concrete is removed from the building, highways and roads and other infrastructure stock via total or selective demolition depending on the construction type. The former process includes techniques such as imploding with explosives, wrecking by crane and wrecking ball, undermining using hydraulic excavators and ramming by dozers with racks made of I-beams or pipes.

Next, waste concrete is sent to C&D, municipal solid waste (MSW) or non-permitted landfills for disposal. Alternatively, waste concrete sent to recycling is further processed by crushing and passing through a vibrating screen to remove the fines. Magnets separate out steel reinforcing materials, which are also recyclable, while aggregates larger than $^3/_8$ inch are fed into a secondary crusher to produce coarse aggregate in the desired size. Recycled concrete pavements yield about 45- 80% usable coarse aggregate (AIA ERG, 1996). The end-uses of waste concrete are predominantly roadbed fill (about 70-80%), as aggregates for new concrete pavements, foundations and products (e.g. pipes and slabs, cast-in-place walls and floors), or clean fill for new construction (AIA ERG, 1996, Renfoe/Noyes Data Corporation, 1979). A new concrete mix can contain 100% recycled coarse aggregate and 10-15% replacement of virgin sand with recycled fines (Klemm, 1995 cited in AIA ERG, 1996). Moreover, recycled aggregates currently account for less than 1% of total demand for construction aggregates and this figure is increasing (Wilburn and Goonan, 1998). With proven economic viability, waste concrete could supplement construction aggregates and free up natural aggregates for higher-valued products, e.g. Portland cement concrete (Wilburn and Goonan, 1998). Overall, the quality of concrete made with waste concrete aggregates is comparable to that made with virgin aggregate materials (Lauritzen, 1991 cited in AIA ERG, 1996). Similarly, concrete roads made with waste aggregates have sufficient plastic and elastic stiffness for use in heavy duty roads. Disadvantages to recycling include greater difficulty in quality control due to contamination and additional energy required for processing and transporting to recycling facility (if necessary) and end-users. Moreover, due to the higher porosity of waste concrete aggregates, more water and cement are required. Nevertheless, recycling is becoming a more popular option. Several trends have encouraged such a climate: increasing landfill costs ($20 – 50 per ton; Lauritzen, 2004 cited in AIA ERG, 1996), shortages in natural aggregates in some regions and stricter C&D landfill regulations. More states are also adopting guidelines for using recycled aggregates. For example, 44 states now allow use of recycled aggregates in road base applications, 15 States for backfill, eight States for Portland cement mix and seven States for top-course asphalt and selected other applications.

7.3 MFA results

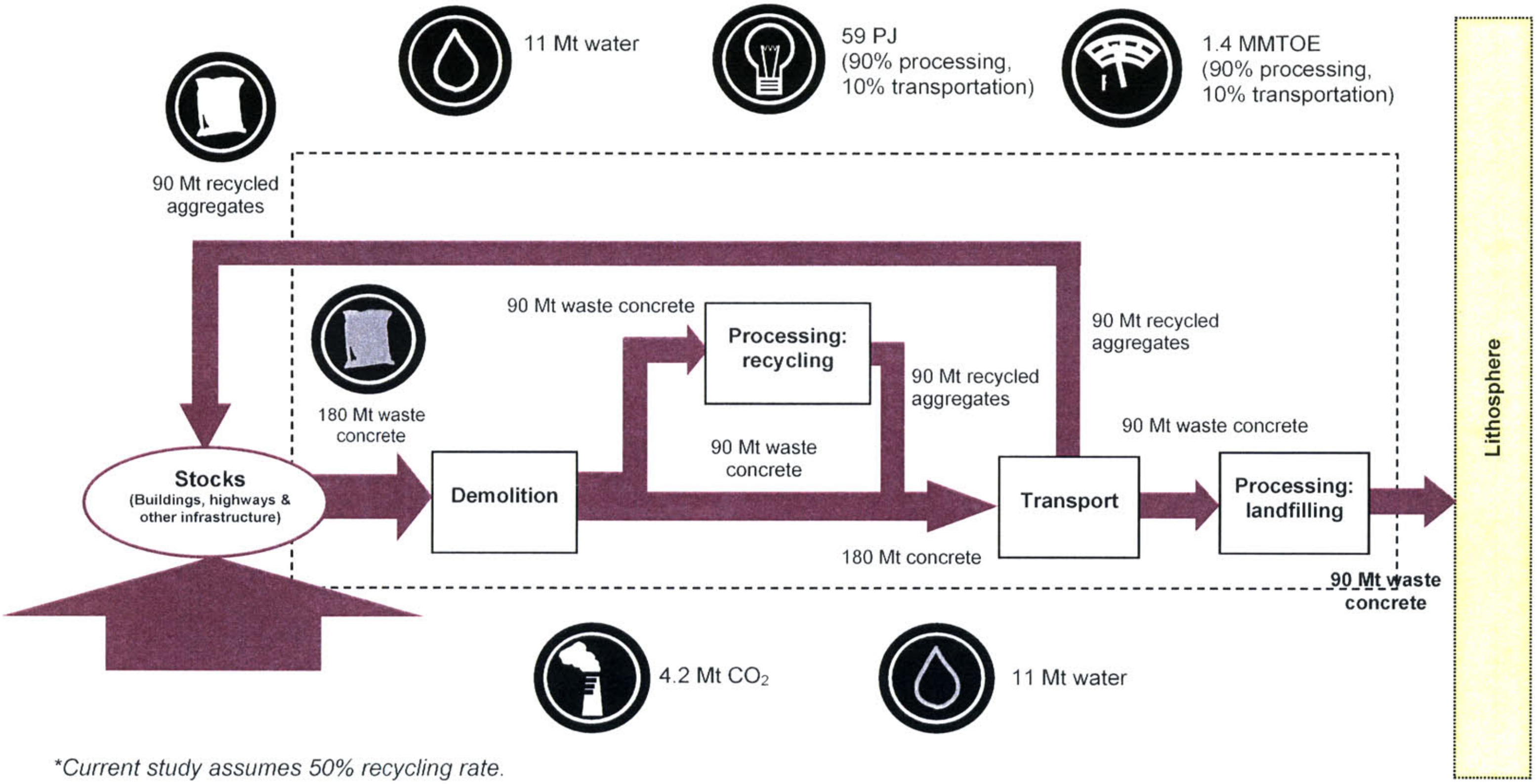
7.3.1 System boundaries

The system in this stage includes: (i) construction, renovation and repair waste from the use of concrete, as described in the previous chapter; and (ii) demolition waste of physical infrastructure at the end of its life. The processes included are:

(xv) Demolition of buildings, highways and roads and other infrastructure
(xvi) Disposal in landfills
(xvii)Recycling into end-uses among buildings, highways and roads and other infrastructure
(xviii) Transportation of
  - construction and demolition waste concrete to landfills
  - construction and demolition waste concrete to recycling facility and end-users

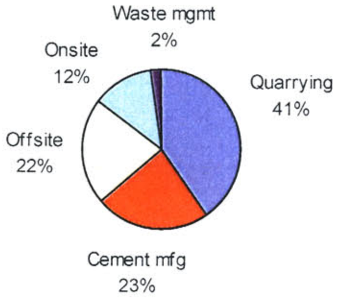
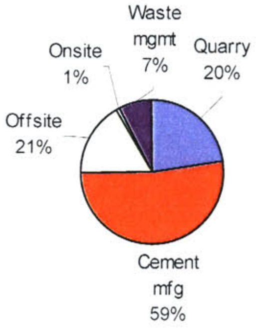
There are large data gaps for this stage of the analysis due to lack of data, particularly for energy and water consumption. Since the processing techniques of waste concrete aggregates and extracted natural aggregates are similar, approximations of energy and water data for this stage are based on coefficients from Chapter 3.

7.3.2 MFA of ‘Waste management of concrete’



Current study assumes 50% recycling rate.

7.3.3 Summary

	Input	Output
Materials	**180 Mt** waste concrete ≡ **1,800 Empire state buildings** *[Total materials throughput (including water) = 191 Mt]*	**90 Mt** recycled aggregates ≡ **900 Empire state buildings** & **90 Mt** waste concrete to landfills
Water	**11 Mt** water ≡ annual water consumption of **160,000 people**  	**11 Mt** effluent
Energy	**59 PJ** or **0.33 GJ/t waste concrete** ≡ annual energy consumption of **1.5 mill people** Processing = **53 PJ**, Transportation = **6 PJ**  Piechart is similar for fuel and CO_2 emissions.	
Fuel	**1.4 MMTOE** ≡ annual fuel consumption of **1 million automobiles**	
Emissions	-	**4.2 Mt CO_2** ≡ annual CO_2 emissions of **93,000 automobiles**

7.3.4 Details of MEFA

(a) Materials

As seen in Figure 7.1, **approximately 180 Mt of waste concrete was produced in 1996. Using the estimate from** Sandler (2003), 61% or 109 Mt of waste concrete is from demolition. This is a reasonable estimate because it is comparable to the 67% demolition waste concrete quoted by Science Council of British Columbia (1991) (cited in AIA ERG, 1996). The remaining 39% (71 Mt) came from construction and renovation. Simply put, 150% more demolition waste is produced than construction and renovation waste. In terms of end-use categories, highways and roads generate slightly more than half of the total concrete waste (54%), followed by buildings (30%).

For this analysis, a recycling rate of 50% is used. Deal (1997) has analyzed the distribution of waste concrete among the recycling end-uses in the United States and found that the majority of waste concrete aggregates are used as subbase in highways and roads (68%), while only 6-7% (estimated at 6 Mt) is used in new cement concrete (see Figure 7.2). Based on this distribution, the author assessed how the recycled concrete was allocated among buildings, highways and roads and other infrastructure (see Table 7.2). For this analysis, it is assumed that the 6 Mt recycled as new cement concrete was used specifically in ready-mixed concrete production (50% for general mix and 50% for road mix).

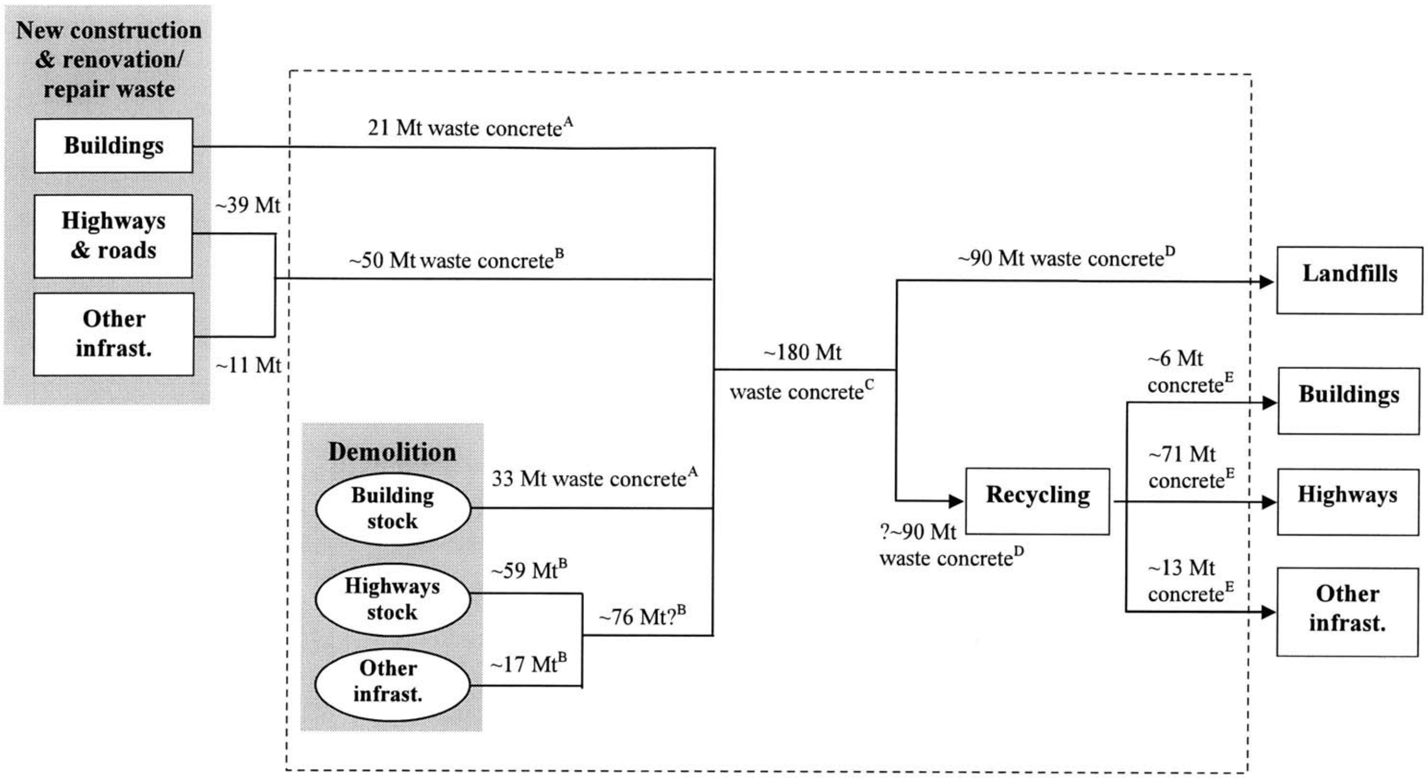


Figure 7.1 Detailed mass flow of 'Waste management of concrete'

- *Waste concrete from buildings includes driveways.*

A: Sandler, 2003

B: Author's estimate using similar percentages for construction and renovation waste and demolition waste of buildings.
Other estimates:
Kelly (1998): estimates that 94.8 Mt crushed cement concrete recycled – which is approximately close to author's estimate.
Wilburn and Goonan (1998); Tepordei 1997: 1.2 Mt of cement concrete recycled into aggregates in 1996 (by natural aggregates producers). This at least gives the lower bound.

C: EPA 2003: Approximately 200 million (short) tons (~180 Mt) of waste concrete generated annually from C&D and public works projects (sources cited in EPA's report: personal communication with William Turley of Construction Materials Recycling Association and Philip Groth of ICF Consulting, 2002; Wilburn and Goonan 1998).
Other estimates: Wilburn and Goonan (1998) estimates 14.5 Mt cement concrete debris produced in 1996 with a recycling rate of 50%. This value seems too low and is likely accounting just for cement concrete debris which is dealt with by natural aggregates producers and do no include construction and demolition waste processors.

D: Author's calculation using:
EPA 2003: 50-60% concrete is recycled (EPA derived from Turley 2002 and Wilburn and Goonan, 1998). Sandler, 2003 also states 50-57% of concrete is recycled. Assuming a recycling rate of 50%, ~90 Mt waste concrete is recycled and ~90 Mt sent to landfills in 1996.

E: Using USGS estimates.

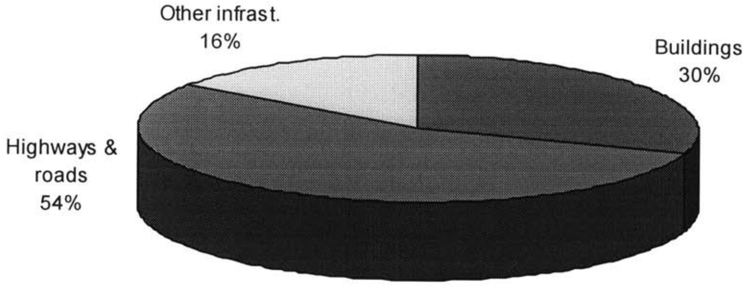


Figure 7.2 Production of waste concrete by concrete end-use categories (by percentage)

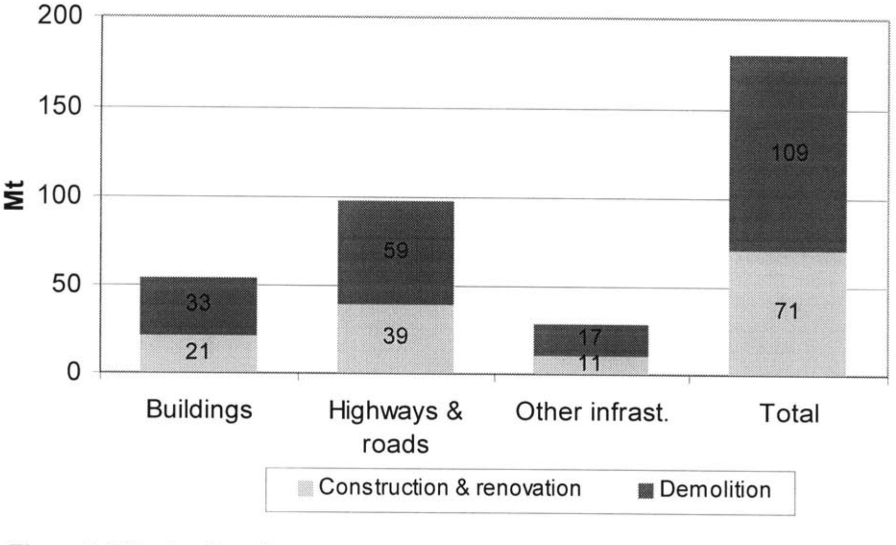


Figure 7.3 Production of waste concrete by concrete end-use categories (in values)

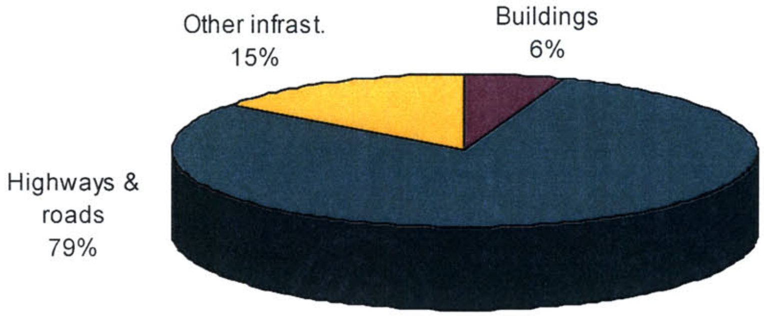


Figure 7.4 Estimated allocation of waste concrete recycled by concrete end-use categories

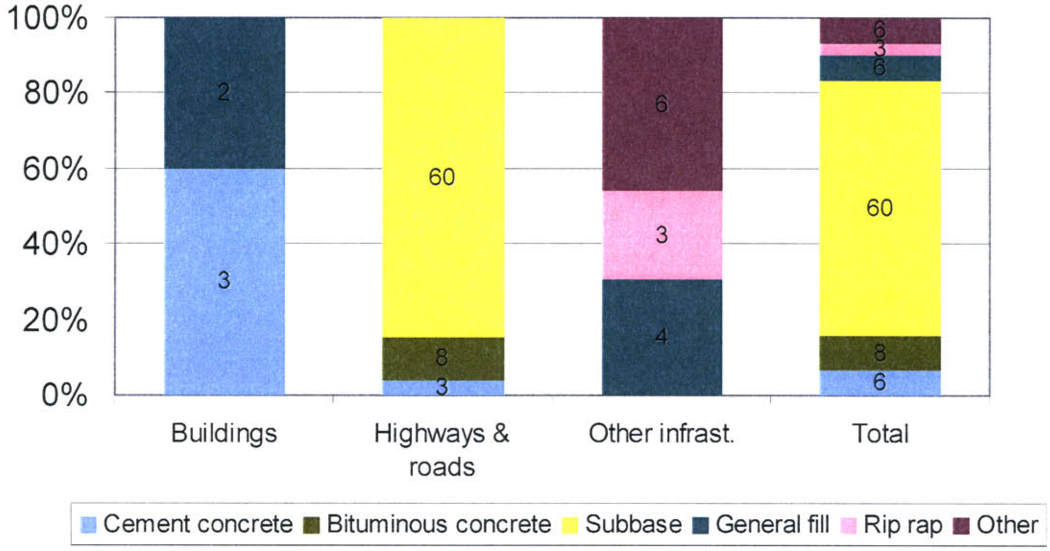


Figure 7.5 Distribution waste concrete recycled by end-uses among end-use categories

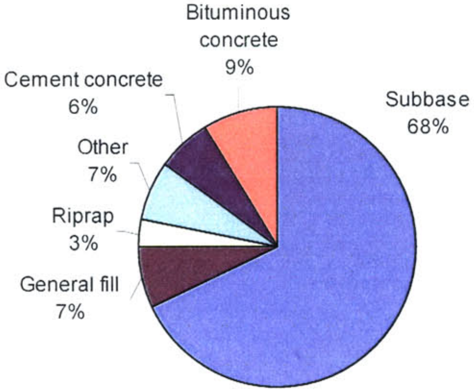


Figure 7.6 Percentage distribution of waste concrete by end use
(Reference: Kelly/USGS, 1998, Deal, 1997)

Table 7.1 Material mass balance of 'Waste management of concrete'

	Total (Mt)	**Buildings (Mt)**	**Highways & roads (Mt)**	**Other infrast. (Mt)**
Inputs				
Construction & renovation waste	~71	21	~39[a]	~11[a]
Demolition waste	~109	33	~59[b]	~17[b]
Total water	~11	~0.70	~8.3	~1.5
Total inputs	**~191**	**~55**	**~106**	**~30**
Outputs				
Waste concrete to land fills	**~90**	**~48**	**~27**	**~15**
Recycled aggregates[c]	**~90**	**~6**	**~71**	**~13**
- New cement concrete	~6	~3	~3	-
- New bituminous concrete	~8	-	~8	-
- Subbase	~60	-	~60	-
- General fill	~6	~2	-	~4
- Rip rap	~3	-	-	~3
- Other	~6		-	~6
Wastewater	~11	~0.70	~8.3	~1.5
Total outputs	**~191**	**~55**	**~106**	**~30**

[a]: By mass balance on concrete types (see Chapter 6).

[b]: Weighed by similar proportions to construction and renovation waste.

c: Assume 50% of total waste is used to produce usable recycled aggregates (i.e. assume processes wastages are already accounted for).

Table 7.2 Allocation of waste concrete end-uses among concrete end-use categories

	Buildings (%)	Highways & roads (%)	Other infrast. (%)	Total (%)
Cement concrete	3[a]	3[a]	-	**6**
Bituminous concrete	-	9[b]	-	**9**
Subbase	-	68[c]	-	**68**
General fill	2.3[d]		4.7[d]	**7**
Rip rap	-	-	3[e]	**3**
Other	-	-	7[f]	**7**
Total	**5.3**	**80.0**	**14.7**	**100**

(Author's allocation based on data from Kelly 1998; Deal 1997).

[a]: Assume ½ cement concrete goes to buildings and ½ goes to highways and roads.

[b]: Assume 100% bituminous concrete goes to highways and roads.

[c]: Subbase materials are typically used in the drainage layer beneath road paving and hence assume 100% used in roads.

[d]: Since 'General fill' includes drainage material for building foundations, leachfields or pipe bedding, assume 1/3 goes to buildings and 2/3 goes to other infrastructure.

[e]: Rip rap is gravel and crushed stone typically used in river beds for erosion protection.

[f]: Assume 'Other' falls under 'Other infrastructure.'

(b) Water

There is no available data on the use of water during the waste management of concrete. The author assumes that half of the waste concrete aggregates require water for processing. Using the ATHENA coefficient[36] for concrete aggregate quarry water from Chapter 3, it is estimated that **11 Mt** of water was used.

(c) Energy

Approximately 59 PJ was used in disposing the waste concrete, which included the decommissioning and demolition, landfill, recycling and transportation sub-processes. This is based on a recycling rate of 50% and a landfill disposal rate of 50%. About 90% of the energy was likely to be used by processing, and the rest for transportation. In this analysis, the transportation energy of waste concrete to landfills and to recycling facility/end-users is assumed to be the same. Subsequently, the comparison shows that recycling uses at least 23% more energy than landfilling, but with a gain of 45-80% of usable aggregates[37] (AIA ERG, 1996) and energy savings from extraction of raw materials. It should also be noted that demolition energy still outweighs recycling energy significantly.

To note, energy data for the waste management of concrete is similarly lacking for the United States. A quote from AIA ERG (1996) states that, "Currently, there is no information on the amount of energy consumed in the reuse, recycling and disposal of

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[36] 234.88 kg water/t aggregates

[37] Assume this rate for concrete pavements also applies to concrete recycling from buildings and other infrastructure.

concrete." To deal with limited data, more comprehensive data from Brown & Buranakarn (2003) are used, though they are in emergy units (the equivalence of solar energy). The percentage distribution of demolition, transportation and landfill based on the emergy data is applied to differentiate between demolition energy and transportation energy from the estimate from Scheuer et al (2003) (see Table 7.4).

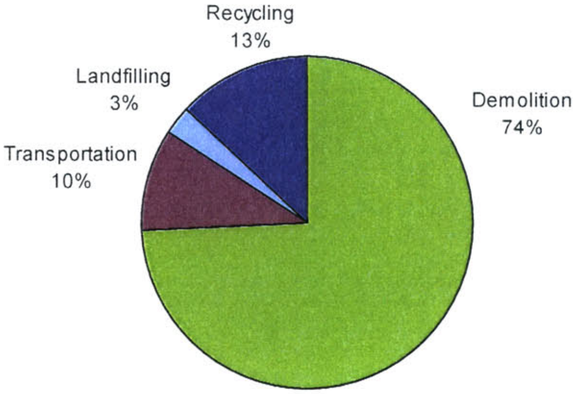

Figure 7.7 Energy use by process type (by percentages)

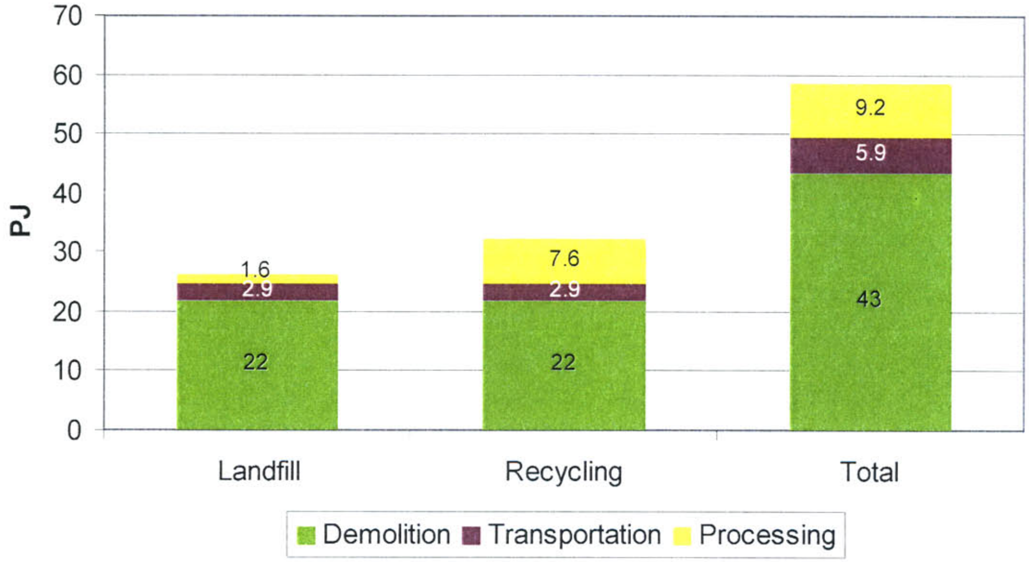

Figure 7.8 Energy consumption by process (in values)

- Assuming that demolition and transportation energy for landfilling and recycling are similar.

Table 7.3 Total energy consumption for waste management of concrete

Energy (PJ)				
Demolition[a]	**Landfill**[b]	**Recycling**[b]	**Transportation**[a]	**Total**
~43	**~1.6**	**~7.6**	**~5.9**	**~59**

[a]: For 180 Mt waste concrete.

[b]: For 90 Mt waste concrete.

Table 7.4 Energy use coefficients for waste management of concrete

	Energy (MJ/t)			
	Demolition	**Transportation**	**Landfill**	**Recycling**
Estimate based on McEvoy (2004)	-	-	-	33.02[a]
Gao et al 2001	-	-	-	84.62
Scheuer et al 2003	273.97[b]		-	-
Current study	**241.4[c]**	**32.61[c]**	**17.58[c]**	**84.62**

[a]: Making a similar assumption as McEvoy that aggregates recycling energy requirements is 75% of a limestone quarry (29.8 GWh to recycle 3,249 kt), concrete recycling energy = 29.8 GWh * 10^6 kWh/ GWh * 3.6 MJ/ 1 kWh / 3,249 kt = 33.02 MJ/t. However, this estimate is not used given that other more representative data is available.

[b]: Given decommissioning, demolition and transportation energy = 4.0 x 10^6 MJ. Assuming it applies for the life cycle mass of building, i.e. 14,600 t, demolition and transportation energy = 4.0 x 10^6 MJ/ 14,600 t = 273.97 MJ/t

[c]: Applying the % distribution of emergy data from Brown & Buranakarn (2003) on Scheuer's estimate: demolition (& sorting) 83%, transportation 33% and landfill 18%, demolition energy = 241.4 MJ/t, transportation energy = 32.61 MJ/t and landfill energy = 17.58 MJ/t.

(d) Fuel

To produce 59 PJ for this stage, **1.4 MMTOE** is required. Most likely, 100% of the energy expended is in the form of diesel fuel.

(e) Emissions

It is estimated that **4.2 Mt CO_2** was emitted. Similar to energy use, processing accounted for 90% (3.7 Mt) and transportation accounted for the rest (0.42 Mt).

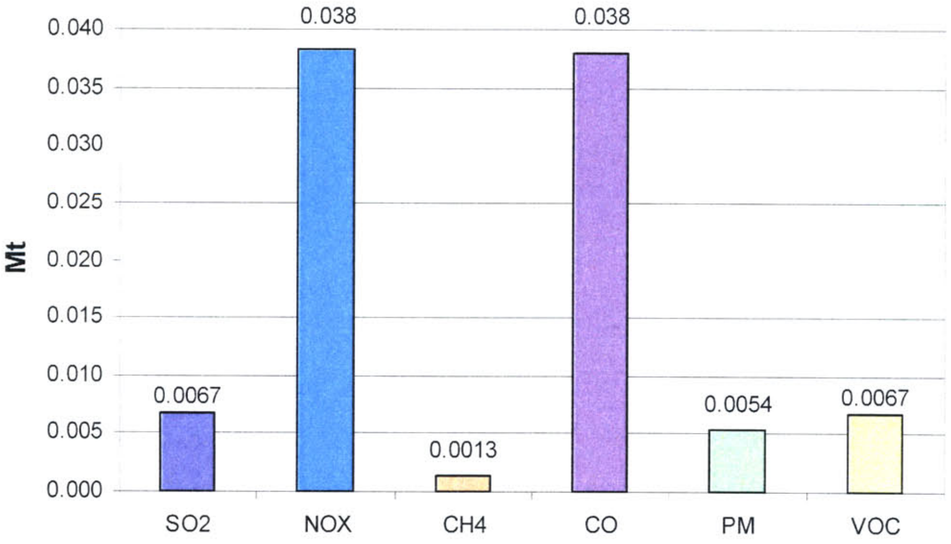

Figure 7.9 Emissions from 'Waste management of concrete' stage

7.4 Preliminary conclusions

1. Demolition of buildings, highways and roads and other infrastructure produce **50% more** waste concrete by mass than from construction and renovation.
2. It is estimated that 54% of the waste concrete was produced from highways and roads, followed by buildings (30%) and other infrastructure (16%).
3. Most of the waste concrete was likely to be recycled back into **highways and roads (79%),** followed by other infrastructure (15%) and buildings (6%).
4. It is implied that the building stock has the lowest waste concrete retention rate **(~10%).** In 1996, buildings produced about 30% of the total waste concrete, but only incorporated 3% of it back into the stock. The remainder was diverted to use in other recycling end-use categories. On the other hand, highways and roads retained about 70% of the waste concrete produced.
5. Only 6-7% of the total recycled waste concrete was used for new concrete production, while road subbase was the most popular use for waste concrete (68%).
6. Assuming that transportation and demolition energy is the same, recycling uses at least 23% more energy than landfilling per unit mass. However, recycling yields 45-80% usable aggregates and energy savings from extraction of raw materials.

The current study is based on several values extracted from literature, including the estimate of 180 Mt waste concrete generated from C&D and public works; the percentage breakdown of the end-uses of recycled concrete aggregates; and waste concrete generated from the construction, renovation and demolition of buildings. All the other values presented in this chapter are estimated based on the assumptions of the author and mass balances. This chapter has presented how waste concrete from construction, renovation and demolition is managed. This concludes the entire lifecycle of concrete in the United States in 1996. The next chapter discusses findings derived from the overview of this study.

CHAPTER 8 DISCUSSION OF MFA RESULTS

8.1 Introduction

This chapter is divided in four sections. The first section presents the summary of the overall material, water and CO_2 flows for the entire life cycle of concrete in the United States, as derived from Chapters 3 – 7. This section also includes an unprecedented application of Sankey diagrams for concrete. The next section compares the MFA results with related studies to establish their validity in terms of mass and energy flows, embodied energy and CO_2 emissions of concrete; while the third section discusses some of the current and potential material management opportunities for each life cycle stage of concrete. The final section shares the main conclusions of this chapter.

8.2 Overview of MFA results

This section presents the overall material, energy and CO_2 flows for the entire life cycle of concrete in the United States. The material flows, water consumption, energy consumption and CO_2 emissions associated with the different physical and chemical transformations of concrete are presented in the following figures.[38] A few key findings are observed:

1. In 1996, the production of 868 Mt concrete required 273 Mt water, 100 Mt recycled aggregates, 96 Mt of cement and SCM and 771 Mt total materials moved. The consumption of concrete or added to stocks was 800 Mt.
2. The total materials moved (919 Mt) and the total concrete added to stocks (800 Mt) are the two largest flow categories (see Figure 8.1).
3. The efficiency of producing concrete is estimated to be 65%. Alternatively, the waste production rate is 35%. Most of the waste is made up of wastewater (44%), followed by mining waste (38%) and concrete production solid waste (18%) (see Figure 8.2).
4. In 1996, every American consumed **5 Mt** of materials, water and fuel[39] to produce **3 Mt** of concrete and **2 Mt** of waste and wastewater[40] over the life cycle of concrete.
5. The quantity of waste concrete recycled internally during the mixing of ready-mixed concrete and the prefabrication of concrete products was significantly larger than the recycling of construction and demolition waste concrete (see Figure 8.2). The ratio of concrete internally recycled to externally recycled can be as high as 16:1.

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[38] Concrete undergoes four types of physical transformations (from lithosphere materials to usable raw materials; to cement; to concrete; to recycled concrete aggregates) and three types of chemical transformations (from lithosphere materials to usable raw materials; to cement; to concrete).

[39] Includes materials moved during mining; cement and supplementary cementitious materials; recycled concrete aggregates; water and fuel (oil equivalent).

[40] Includes all solid waste (mining; production; construction, renovation and demolition waste) and wastewater generated.

6. Extraction of cement and concrete raw materials is the most water-intensive in absolute values, followed by off-site production of concrete (ready-mixed concrete and concrete products) and cement manufacturing (see Figure 8.8). The dominant form of water effluents is wastewater.
7. Cement manufacturing is the most energy-intensive in absolute values (51% of total), consuming as much energy as all the other stages added together (see Figure 8.11).
8. Cement manufacturing emits the most CO_2, equivalent to the sum of CO_2 emitted from the other four stages (see Figure 8.16).
9. It is postulated that the composition of C&D waste in the United States is **30% building-related, 55% road-related and 15% other infrastructure-related.**
10. The total transportation energy can be as high as 14% of the total energy consumption during the life cycle of concrete (see Figure 8.13).

In summary, each stage can be ranked according to its contribution in each category:

Materials losses (solids): Extraction stage > Waste management stage > Use of concrete > Cement manufacturing > Off-site production of concrete

Water consumption: Extraction stage > Off-site production of concrete > Cement manufacturing > Use of concrete > Waste management stage

Energy consumption (including transportation in each stage) and CO_2 emissions: Cement manufacturing > Extraction stage > Off-site production of concrete > Waste management stage > Use of concrete

Energy consumption (transportation as separate stage): Cement manufacturing > Extraction stage > Off-site production of concrete > Transport stage > Waste management stage > Use of concrete

In addition to these new key findings, the application of Sankey diagrams for a compound, in particular concrete, is unprecedented (see Figure 8.2). Sankey diagrams are typically used for substance flows (for example lead – Socolow & Thomas, 1997[41], zinc—Brunner and Rechberger, H., 2001 cited in Brunner, 2003). Since most substances have short residence times, the Sankey diagrams are ideal for capturing relatively constant quantities of inputs entering and outputs leaving the economy, akin to 'steady state' flow. On the other hand, the Sankey diagram in this study is modified to account for the long residence time of concrete and the physical and chemical transformations of raw materials, water and recycled aggregates to concrete, as opposed to tracking one specific substance throughout the entire diagram. The stark difference in residence times between concrete and substances such as lead is evident in the distorted additions to stock flow and recycled flow (as represented by the elliptical flow). A typical Sankey diagram for a substance shows an equivalent quantity of recycled flow leaving the stock as the additions to stock flow (i.e. a symmetrical elliptical flow).

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[41] Cited in U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flows (1999)

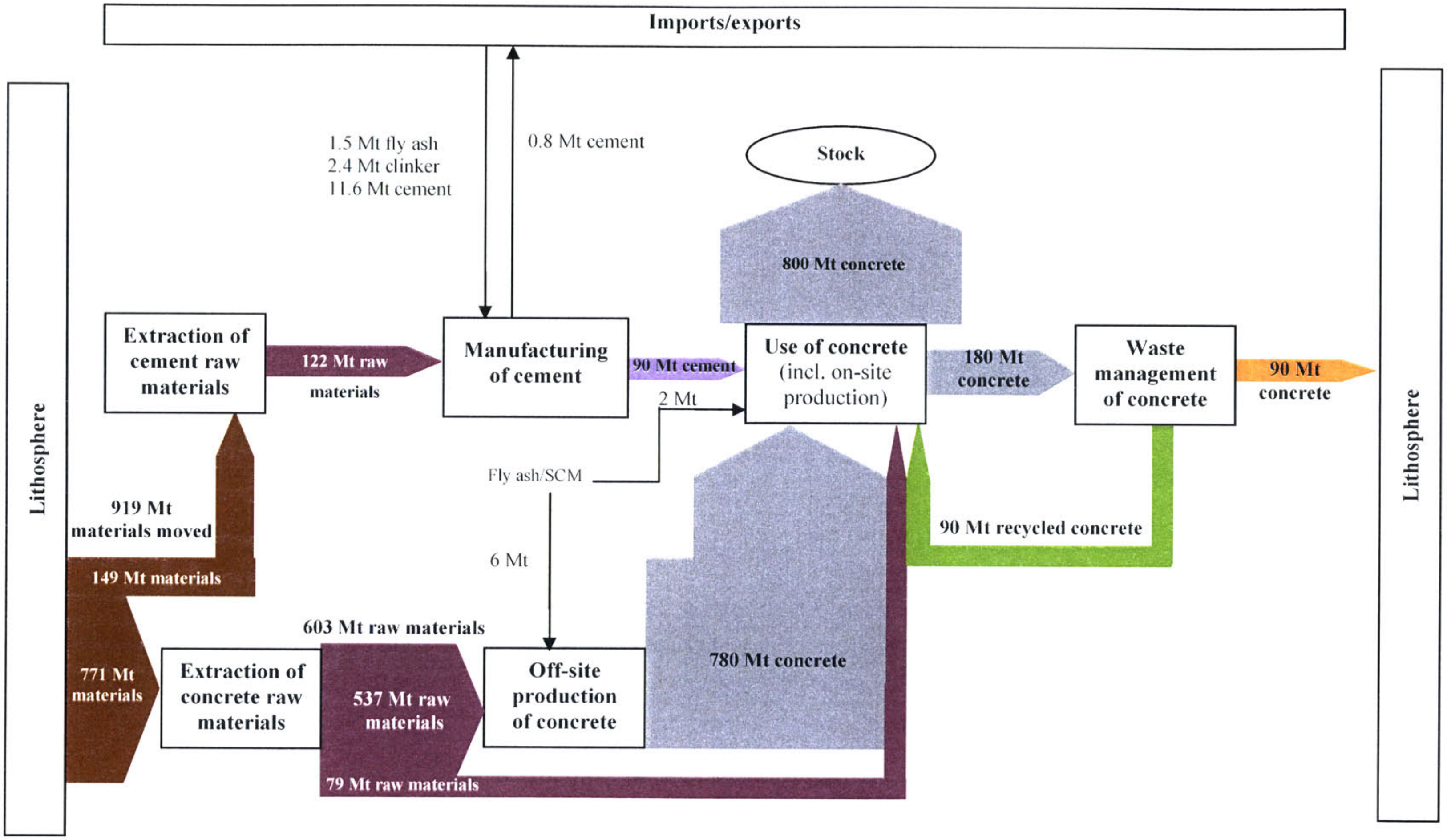

Figure 8.1 MFA mass balance of concrete in the United States in 1996 (excluding water)

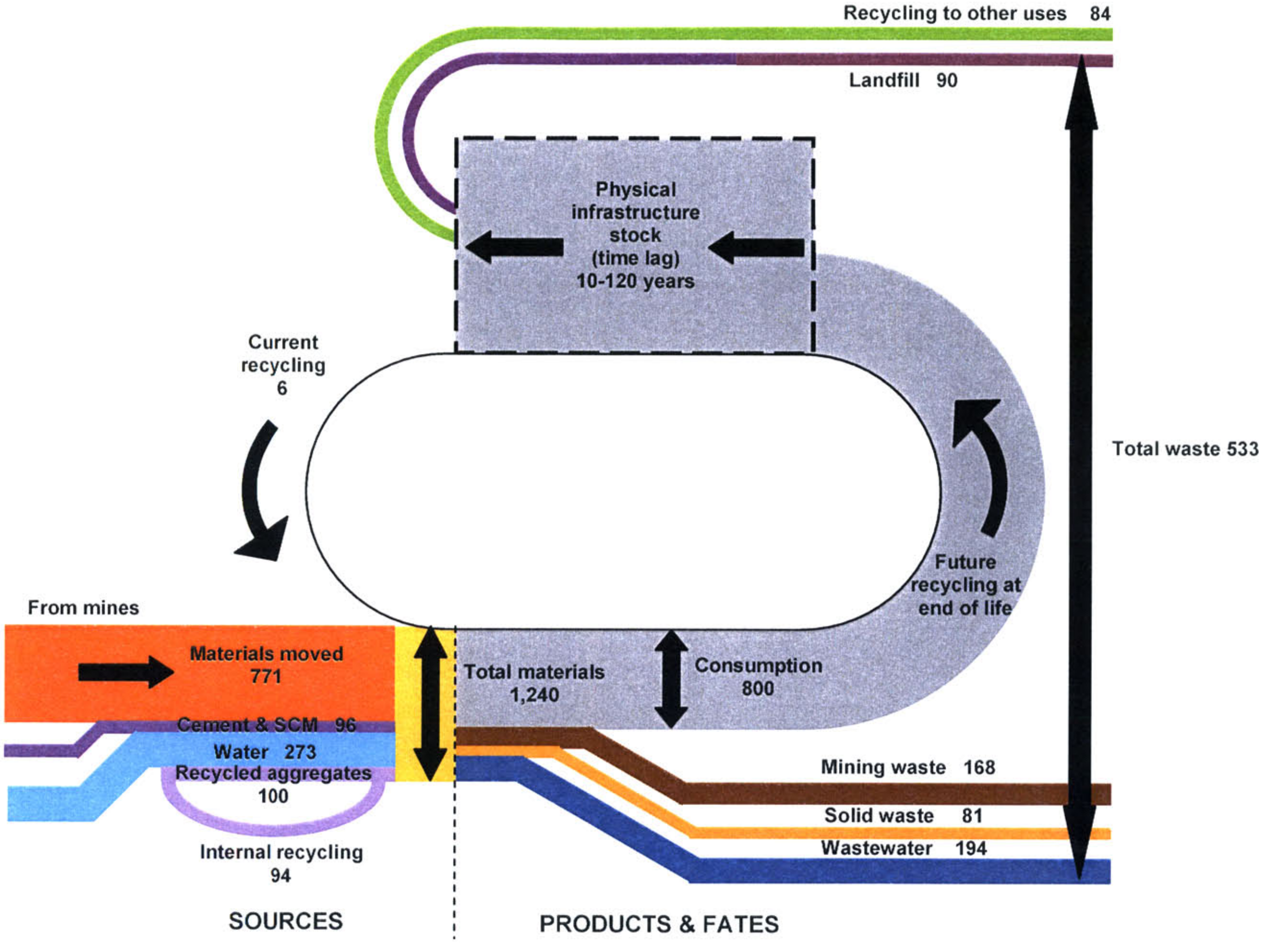

Figure 8.2 Sankey diagram of 1996-1997 concrete flows in the United States in Mt/year (excluding air and fuel)
(Reference: '1993 – 1994 Lead flows' by Socolow & Thomas, 1997 cited in
U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flows, 1999)

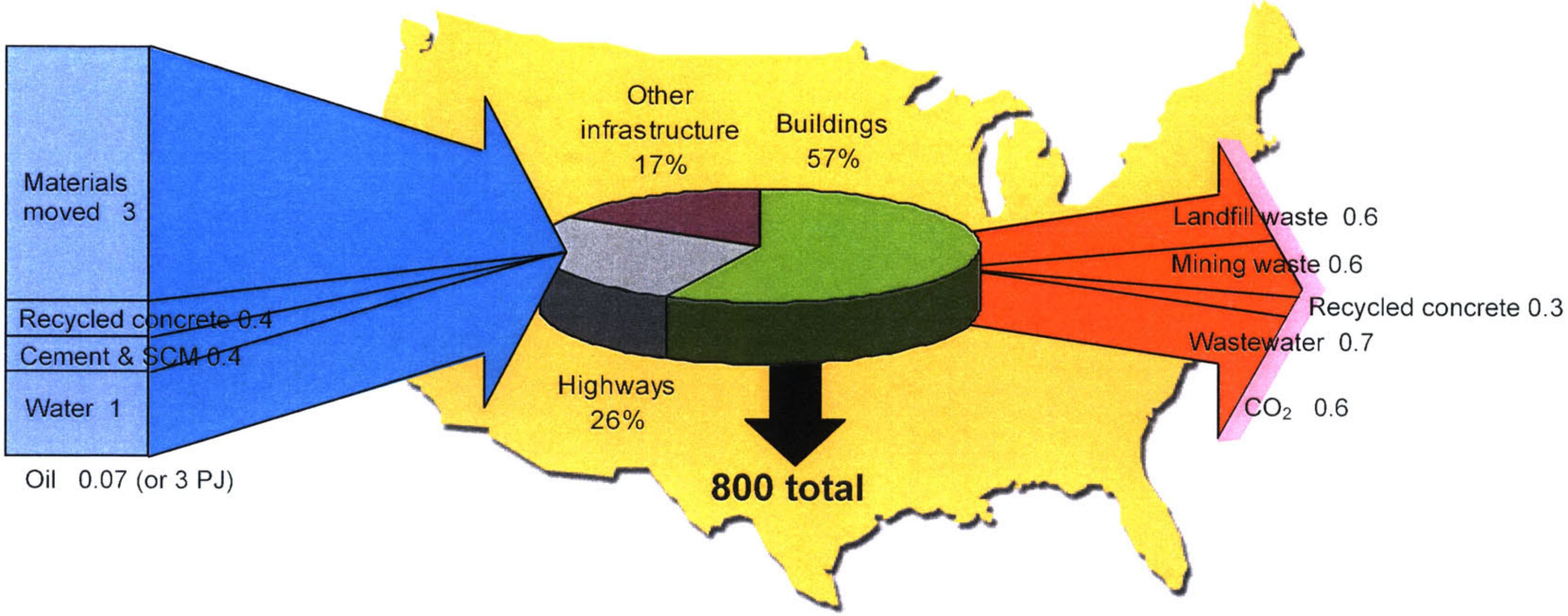

Figure 8.3 Per capita materials consumption for the life cycle of concrete in the United States in 1996 in Mt (excluding oxygen)
(Reference: Brunner et al, 1994)
Photo credit: http://graphicmaps.com/webimage/usimages/48shapes/noborder/87a/shadow/587yeld.htm)

Notes: This is not a mass balance. Recycled concrete as inputs consist mainly of concrete recycled internally during concrete production. Recycled concrete as output is dominantly waste from the construction, renovation and demolition of buildings, highways and roads and other infrastructure.

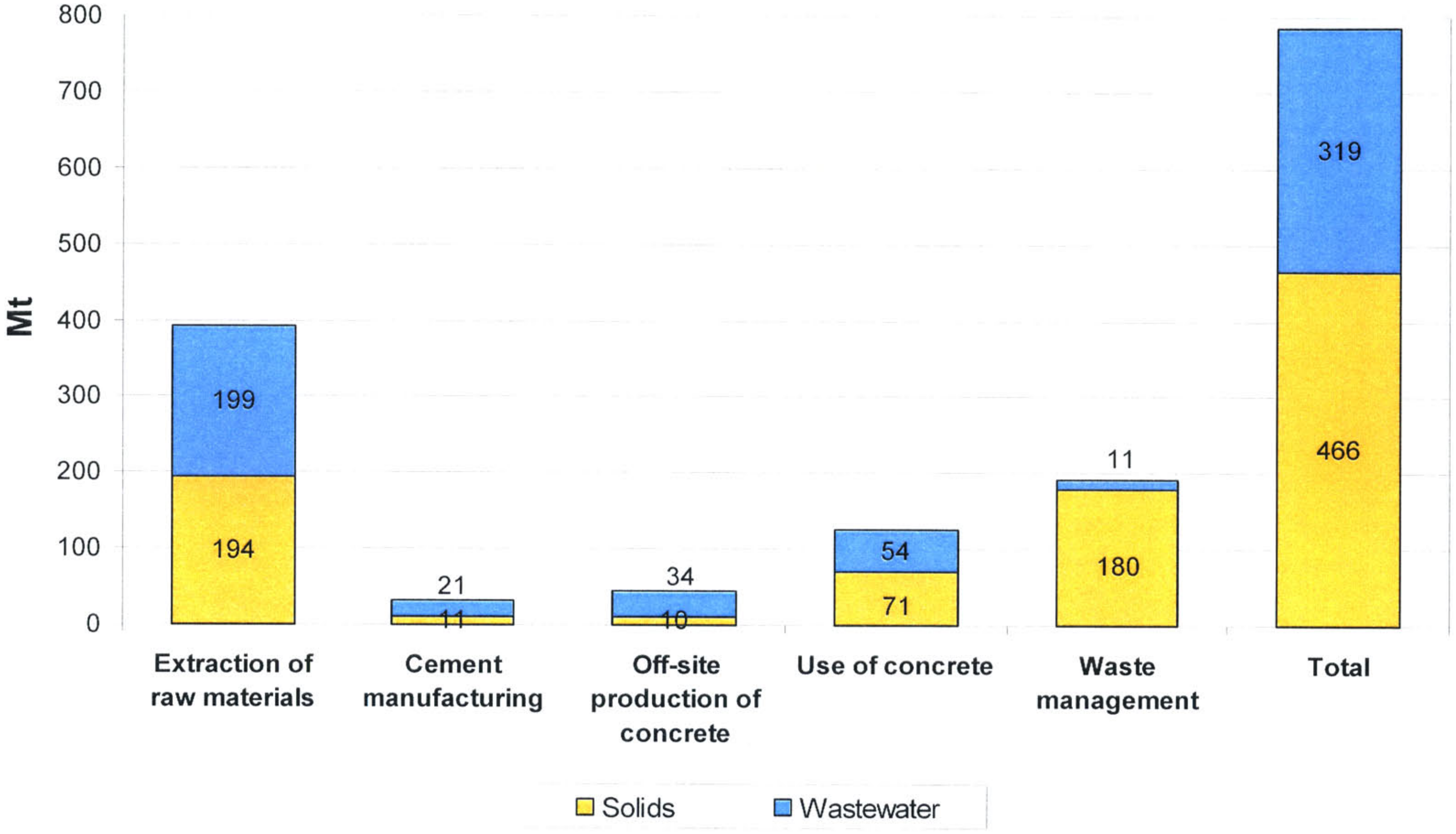

Figure 8.4 Total waste flows of concrete production in the United States in 1996 by life cycle stage
(Note: Waste management includes construction and renovation waste from 'Use of concrete' and demolition waste)

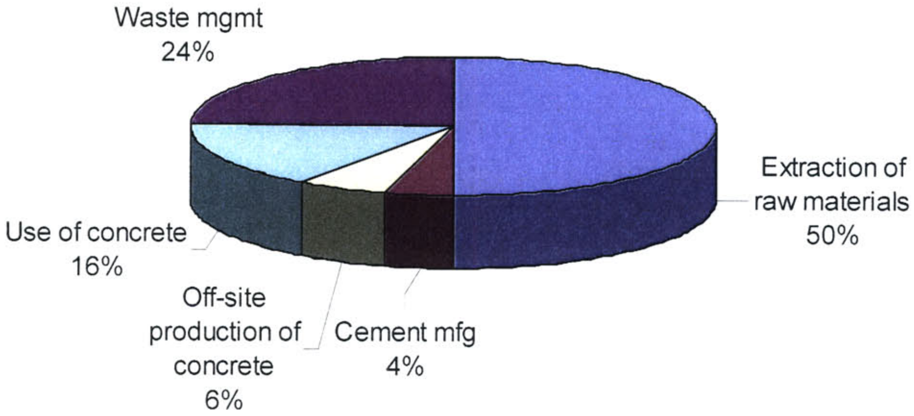

Figure 8.5 Total waste flows of concrete production in the United States in 1996 by stage (solid waste and wastewater, by percentages)

(Note: Waste management includes construction and renovation waste from 'Use of concrete' and demolition waste)

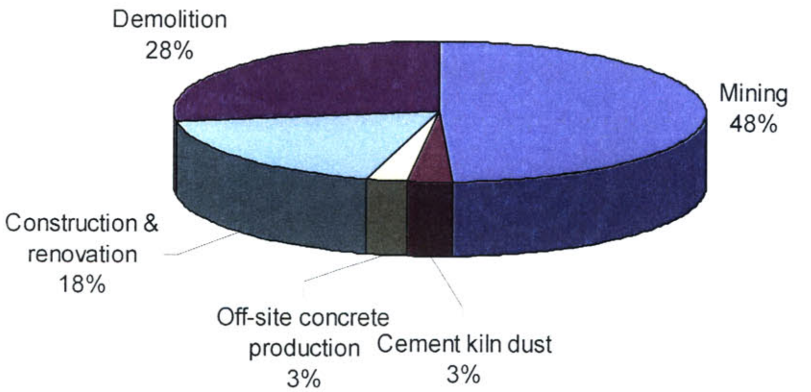

Figure 8.6 Composition of solid waste flows of concrete production in the United States in 1996 (by percentages)

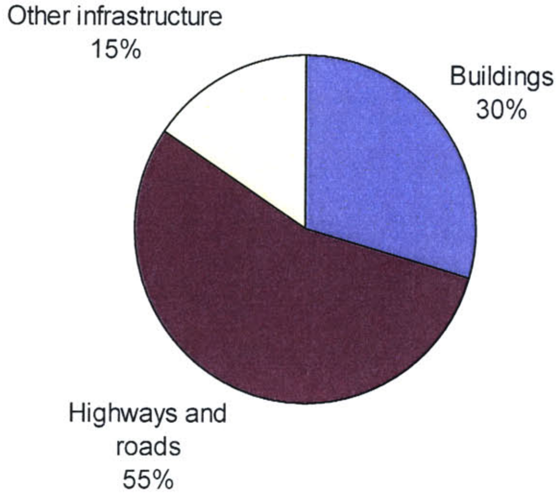

Figure 8.7 Estimated composition of construction and demolition waste by end-use category
(Derived by author as weighted by concrete flows entering into the stocks)

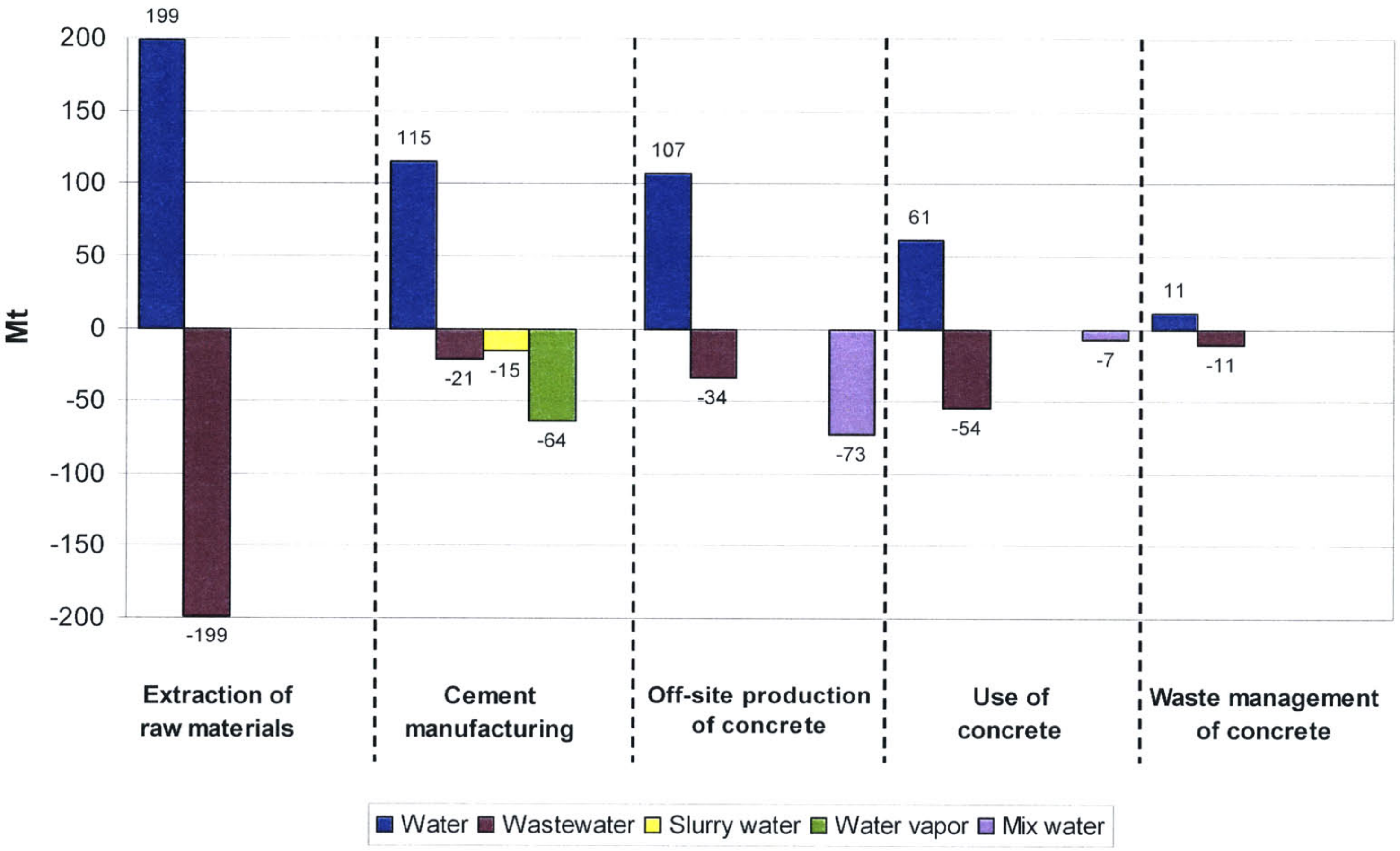

Figure 8.8 MFA water mass balance of concrete production in the United States in 1996

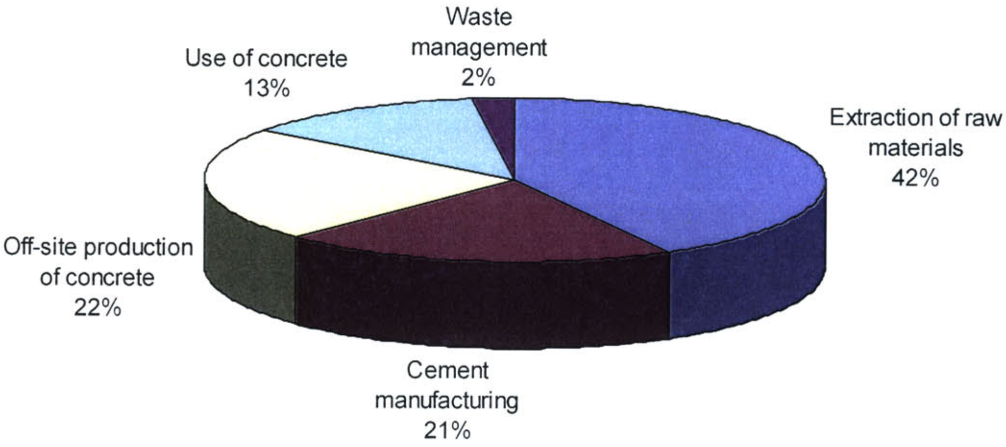

Figure 8.9 Water consumption for the life cycle of concrete in the United States in 1996

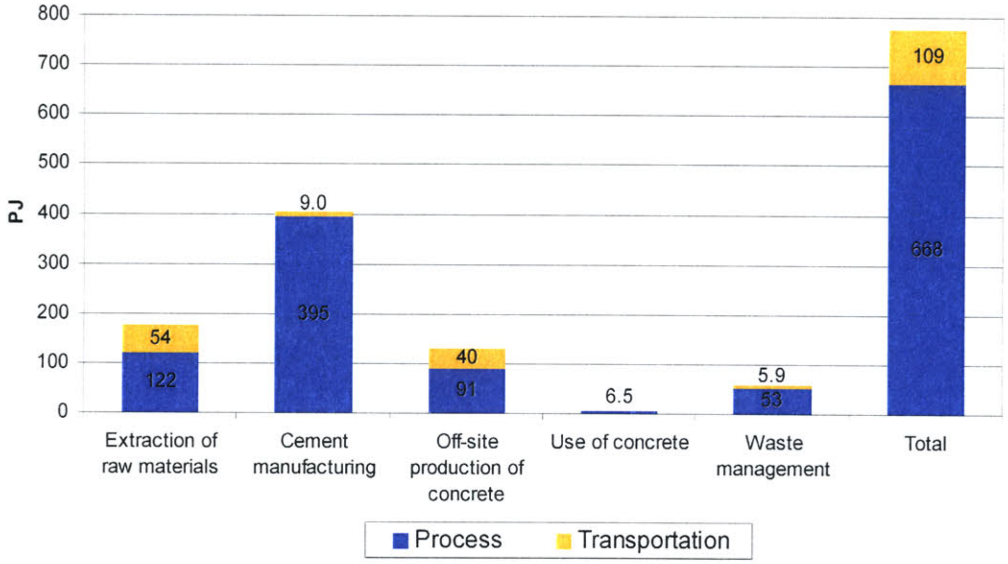

Figure 8.10 Energy consumption for the life cycle of concrete in the United States in 1996 by stage (including transportation, in values)

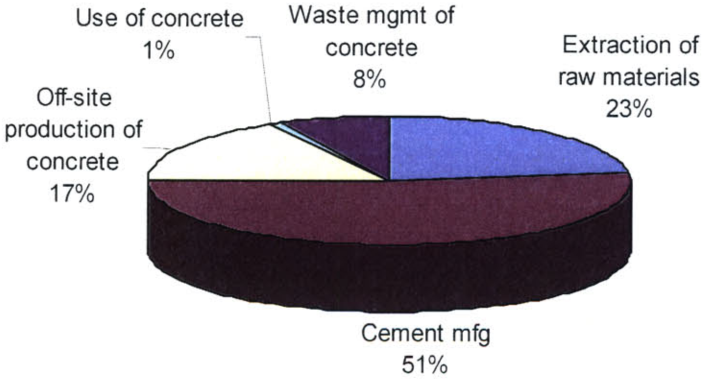

Figure 8.11 Energy consumption for the life cycle of concrete in the United States in 1996 by stage (including transportation, by percentages)

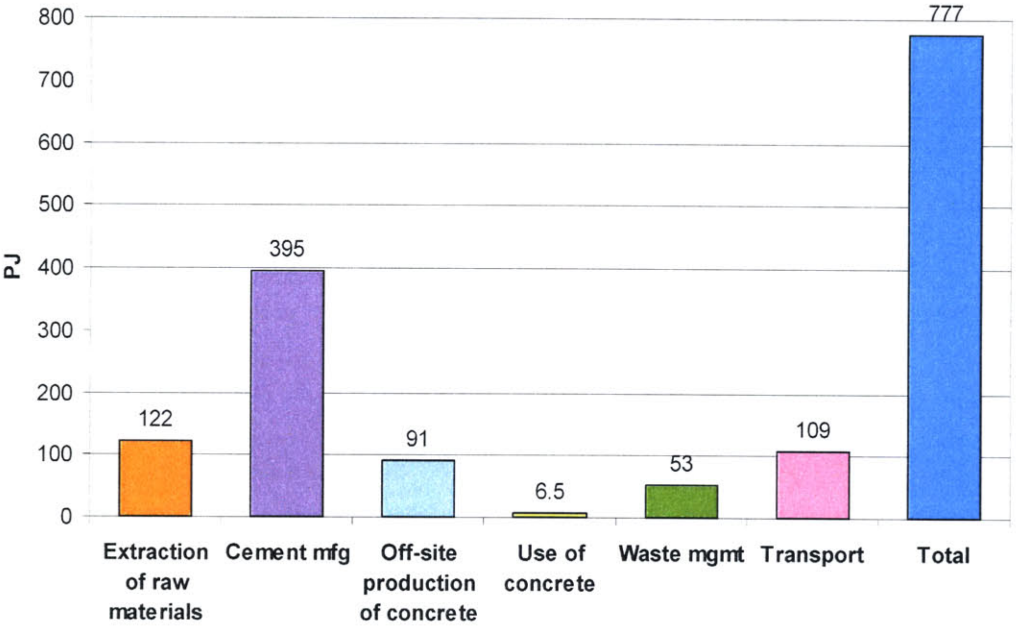

Figure 8.12 Energy consumption for the life cycle of concrete in the United States in 1996 by process (transportation from all the life cycle stages treated as a separate stage, in values)

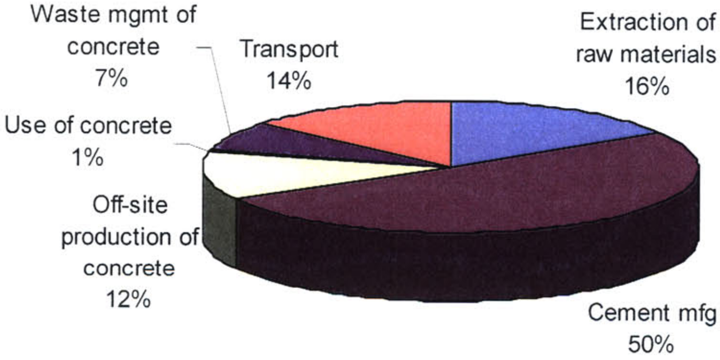

Figure 8.13 Energy consumption for the life cycle of concrete in the United States in 1996 by process (transportation from all the life cycle stages treated as a separate stage, by percentages)

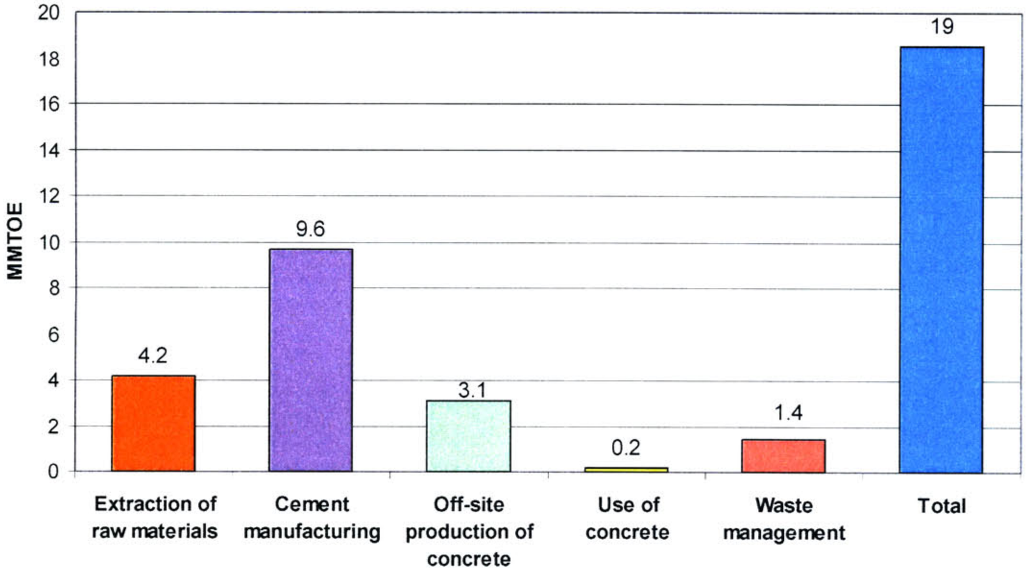

Figure 8.14 Fuel consumption for the life cycle of concrete in the United States in 1996 by process

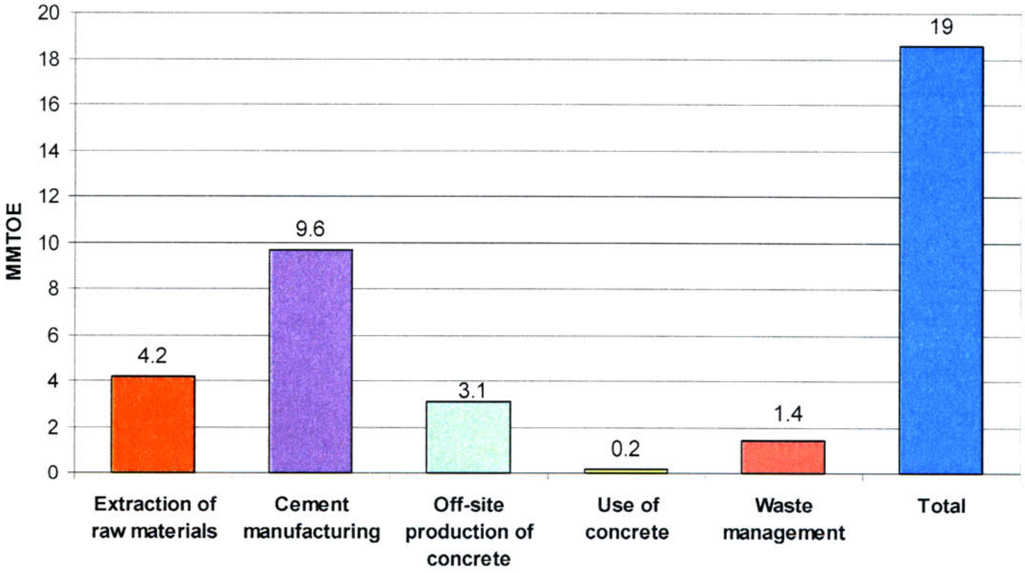

Figure 8.15 Total CO_2 emissions for the life cycle of concrete in the United States in 1996 by stage (in values)

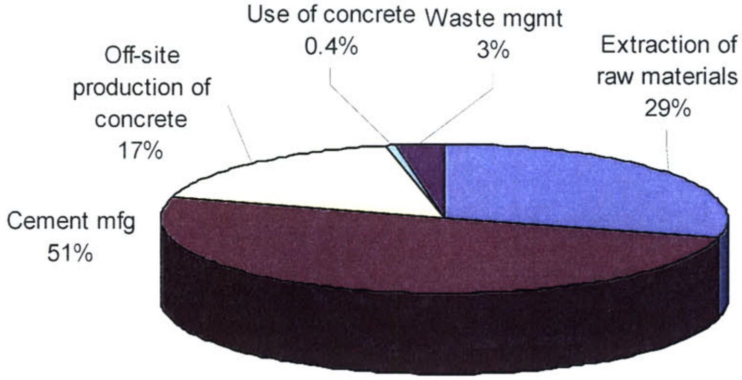

Figure 8.16 Total CO_2 emissions for the life cycle of concrete in the United States in 1996 by stage (by percentages)

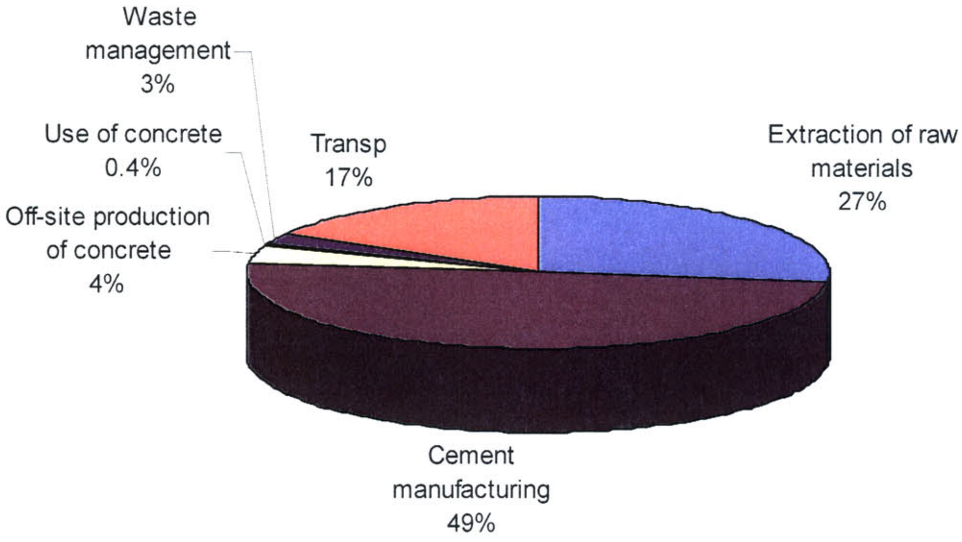

Figure 8.17 Total CO_2 emissions for the life cycle of concrete in the United States in 1996 by stage (transportation from all the life cycle stages treated as a separate stage)

8.3 Validity of MFA results through comparisons

In this section, comparisons of the current study are made with the mass flows, energy flows, embodied energy and carbon dioxide emissions from other literature.

8.3.1 By mass flows

(i) Hidden flows

"The Weight of Nations" reported that 61 metric tons of hidden flows per capita were generated in 1996 (World Resources Institute, 2000). By comparison with this study, it is estimated that 1.2% of hidden flows per capita were attributed to the extraction of cement and concrete raw materials (or 0.73 metric tons per capita).

(ii) Quantity of cement and concrete consumed

The quantity of concrete consumed in the United States in 1996 as estimated from the current study is compared with other estimates (extrapolated to 1996 when necessary).

Table 8.1 Comparisons between the quantity of cement and concrete used in the United States in 1996

	Current study (2005)	**Other estimates**
Cement use for highways & roads	23.9 Mt cement	35.8 Mt cement (Kelly, 1998)
	Kelly's estimate is **50% greater**. Kelly distributes cement use among two main end-use categories (buildings and roads) versus three in this study.	
Volume of concrete produced	383 mill m^3 (or 352 mill m^3 available for use after accounting for construction waste)	265.6 mill m^3 (Lemay, 1995 cited in AIA ERG, 1996; USGS MCS 1995)[42]
	Current study estimate is **33 – 44% larger** than Lemay's estimate.	
Mass of concrete produced	868 Mt (or 800 Mt available for use after accounting for construction waste)	638 Mt concrete (Kelly, 1998)
	Current study estimate is **25 – 36% larger** than Kelly's estimate. Again, three end-use categories are used instead of two in Kelly's study. The concrete mix is also dependent on the concrete type, while Kelly used a standard concrete mix of 3.1 gravel: 2.6 sand: 1 cement: 0.55 water.	
Volume of ready-mixed concrete produced	299 mill m^3	260 mill m^3 (PCA)[43]
	Current study estimate is **15% larger** than PCA's estimate.	

In general, the current study estimates tend to be the on the high end (15 - 44% larger.) The degree of aggregation appears to be a key factor. This study tends to be more specific in terms of allocation among end-use categories and concrete mix (which affects the computation of volume and mass of concrete produced). In addition, there might be differences in the types of concrete included in the estimates (roads, buildings, etc.)

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[42] Interpolated from Lemay's 1994 estimate of 268 mill m^3 using apparent consumption of 91.2 Mt cement from USGS.

[43] Produced annually for use in roads and highways, parking lots and garages, high-rise buildings, dams, floors, etc. http://www.cement.org/tech/

8.3.2 By energy flows

(i) Concrete production

The current study uses average coefficients from various sources, including the PCA LCI of Portland concrete. It is found that the percentage distribution of embodied energy among the stages is comparable with that of PCA LCI of Portland concrete (see Figure 8.18 and Table 8.2).

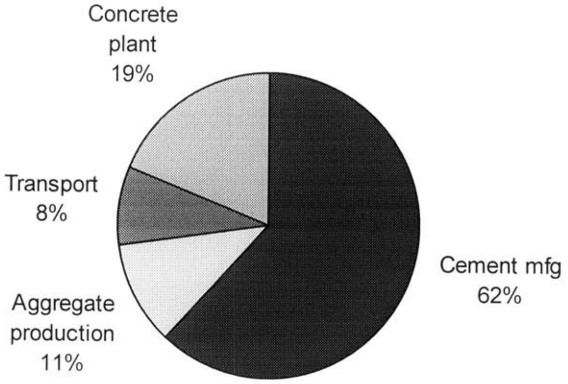

Figure 8.18 Embodied energy of ready-mixed concrete by process

Table 8.2 Comparison of embodied energy of ready-mixed concrete

	PCA, LCI of Portland concrete (20 MPa ready-mixed concrete)		Current study (Ready-mixed concrete)	
Process	**Embodied energy (GJ/m^3 concrete)**	**Percentage**	**Embodied energy (GJ/m^3 concrete)**	**Percentage**
Cement manufacturing	1.18	70%	1.02[a]	62%
Aggregate production	0.13	8%	0.18[a]	11%
Transportation	0.12	7%	0.14[a,b]	8%
Concrete plant	0.25	15%	0.31[c]	19%
Total for concrete	**1.68**	**100%**	**1.65**	**100%**

[a]: Based on 880 mill m^3 of concrete thereotically produced.
[b]: Similar to PCA study: transportation of raw materials to concrete plant.
[c]: Based on 209 mill m^3 of general ready-mixed concrete.

(ii) Life cycle of buildings

The energy expended for building material production is often factored in the energy consumed throughout the life cycle of buildings for the production, maintenance, operation and demolition stages. The influence of materials on the total life cycle energy consumption of buildings is briefly described. Direct comparisons are not possible due to different system boundaries, levels of aggregation and specificity of one material versus various materials in a structural system or a building. Kotaji et al (2003) estimated that the use phase in conventional buildings represents approximately 80 – 90% of lifecycle energy use, while 10 – 20 %[44] consumed by materials extraction and production and less than 1% through end-of-life treatments (Kotaji et al, 2003). On the contrary, the energy impacts of building materials are not only limited to the extraction and production stages. The type of construction system and how the building materials are used also influence the demolition energy required due to the ease of demolition or deconstruction. Another study has shown that demolition energy or end of life energy can be as high as 37%[45] (Lalive d'Epinay, 2000 cited in SETAC, 2003). In other words, the production and use of building materials can directly and indirectly influence the life cycle energy use of buildings by at least 20%

8.3.3 By embodied energy

(i) Extraction of raw materials

One Norwegian study found that though aggregates make up about 80% of concrete products [by mass], they account for less than 3% of the energy consumption and emissions released (Vares and Häkkinen, 1998). This study found that aggregates (taken to be concrete raw materials) account for 11 - 16% energy consumption[46] and 19% CO_2 emissions[47] from the extraction stage to use of concrete stage. This can be attributed to differences in system boundaries.

(ii) Manufacturing of cement

Cement accounts for approximately 70% of embodied energy up to the concrete plant gate (PCA LCI of Portland Concrete, 2002). From this study, cement accounts for 62% embodied energy (including transportation energy). The difference may be accounted by the types of data sources used in estimating the energy consumption by cement manufacturing. For this study, five different sources were used.

(iii) Ready-mixed concrete production (off-site)

Through this MFA, the embodied energy of ready-mixed concrete (including transportation) is estimated to be 1.65 GJ/m^3 ready-mixed concrete (see Table 8.2). This value is within the same range as other estimates: 1.57 GJ/m^3 (Fortinek, 1993 cited in AIA ERG, 1996); 1.68 GJ/m^3 (PCA LCI of Portland concrete, 2002). Though some earlier studies had a higher value of 3.58 GJ/m^3 (Hannon et al, 1976 cited in AIA ERG, 1996).

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[44] Thomark (2000) quote similar figures: 10-15% of total energy consumption through the lifecycle of a building is attributed to materials.

[45] Based on a worst-case end-of-life scenario for a good energy performance Swiss office building.

[46] Lower bound does not include transportation energy, while upper bound does.

[47] Percentages are similar when transportation energy is included or excluded.

8.3.4 By carbon dioxide emissions

(i) Cement

In this study, the CO_2 emissions from cement manufacturing are based on national statistics and calculations using available coefficients from LCAs and LCIs. Therefore, they are inherently comparable with most studies. One comparison which can be made is the difference in including CO_2 from the extraction stage. If is found that the CO_2 emissions of cement increased by 11% when the extraction stage (including associated transportation emissions) is included.

Raw materials directly → cement = **1.0 kg CO_2**/ kg cement
Extraction stage → cement manufacturing = **0.91 CO_2**/ kg cement

(ii) Concrete

The following values are found using this study, where the lower bound does not include transportation.

For off-site production only and excludes the placing of concrete during use,
Extraction stage → concrete production (all types) = **0.15 kg** CO_2/ kg concrete

For on-site and off-site production up to the placing of concrete during use,
Extraction stage → concrete use (all types) = **0.15 - 0.18 kg** CO_2/ kg concrete

For the entire life cycle of concrete,
Extraction stage → disposal stage (all types) = **0.18 kg** CO_2/ kg concrete

For off-site production only and includes the placing of concrete during use,
Extraction stage → concrete use (ready-mixed concrete) = **0.15 kg** CO_2/ kg ready-mixed concrete

Vold and Rønning (1995) indicated that 0.14 kg CO_2/ kg concrete for off-site production and excludes the placing of concrete. This compares well with the 0.15 kg CO_2/kg concrete found in this study (the first value listed).

8.4 Discussion of materials management opportunities

8.4.1 Extraction of raw materials

To reduce the quantity of hidden flows incurred in the extraction stage, a straightforward approach is to increase the use of recycled concrete aggregates in concrete production. Currently, the single most dominant end-use of recycled concrete aggregates is road subbase, while a mere 6-7% is used for new concrete production (Kelly, 1998; Deal, 1997). In reality, this demonstrates that it is more economical and technically feasible to downcycle waste concrete, instead of processing waste concrete more intensively to produce high quality aggregates for use in concrete. An even better approach to recycling may be demand-side management of concrete through adaptive reuse, and improved selective demolition and salvaging techniques to increase the materials effectiveness of concrete instead of reducing its throughput. This results in less waste being diverted for disposal and recycling and lessens the demand for aggregates, cement, water and energy in general. In addition, measures to minimize water consumption through recycling or other processing techniques should be explored since this stage is the largest water consumer.

8.4.2 Manufacturing of cement

Four concerns are discussed: (a) energy consumption, (b) CO_2 and greenhouse gas emissions, (c) CKD generation and (d) production of blended cements

(a) Energy consumption

Compared to the average cement energy intensity in the United States for the past decade, 1996 is found to be a representative year (see Figure 8.19). Historically, the cement industry has been investing heavily in energy-efficient technologies to reduce energy costs, which account for 30-40% of the production costs (van Oss/USGS 1996) and is approaching an energy efficiency saturation point.[48] Around 80% of the cement kilns are dry-process, which are more energy-efficient than wet-process kilns and 60% include preheaters and/or precalciners.[49] Martin et al (1999) have identified various technologies for a 40% improvement in energy efficiency. However, high capital costs and low energy costs limit the economic potential to 11% and CO_2 emission reduction potential to around 5% (Worrell et al, 2003; Martin et al, 1999). On the contrary, the (electric and total) energy intensity per unit of cement has risen slightly for the past few years (see Figure 8.19) (Jacott et al, 2003). This is driven by a switch to coke, petroleum coke and alternative waste fuels due to the changing prices of natural gas, which results in a decrease in fuel efficiency and slower efficiency gains.

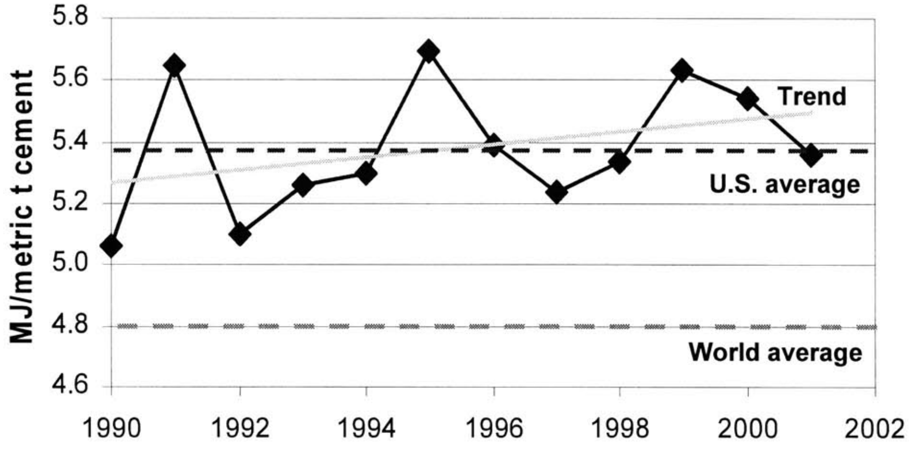

Figure 8.19 U.S. energy intensity of cement (1990 – 2001)
(References: Jacott et al 2003, Worrell et al 2001)

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[48] As pointed out by the work of Martin et al (1999) and comparisons with the energy intensity of cement in the European countries.

[49] Estimated using percentages from PCA LCI of Portland Cement 2002.

(b) CO_2 and greenhouse gas emissions

In 1996, the CO_2 emissions of the cement industry are approximately 1.4% of the total U.S. CO_2 emissions (from energy consumption and industrial process).[50] As mentioned earlier, the advanced technologies could offer only a 5% CO_2 emission reduction potential within economic constraints (Worrell et al, 2003; Martin et al, 1999) and unit CO_2 from calcination could not be reduced (van Oss/USGS, 1996). Other recommended measures include the replacement of high-carbon fuels with low-carbon fuels (e.g. natural gas) and the use of blended cement, which could reduce total CO_2 emissions by 16% (Worrell et al, 2003). In addition, fluidized bed technologies, which produce a turbulent mixing of gas and solids for more efficient combustion, are being implemented. Due to the reliance on coal, petroleum coke and increasingly waste tires, Jacott et al (2003) postulated that increases in greenhouse gas emissions per tonne cement and in total are likely. In addition, dioxins, furans and heavy metals have also increased due to the fuel combustion of hazardous wastes since 1993 (Jacott et al, 2003).

Furthermore, carbon tax on fuels and CO_2 emissions trading are of great relevance to the cement industry. In 1996, a U.S. Department of Energy study showed that the fuel taxes would decrease the price competitiveness of domestic cement relative to imported cement. Consequently, the industry could lose about 15 – 24 Mt of production capacity and imports would increase by at least 100% to supplement the cement demand (Nisbet, 1996 cited in Van Oss/USGS, 1996). Moreover, the cement industry could trade carbon emission allowances with other entities, provided that it is more cost-effective than implementing advanced emission controls or switching to a fuel composition with a higher natural gas percentage. Currently, CO_2 emissions are traded at $20-30 per (short) ton of carbon[51], which means that the buying price for the cement industry is $6 - $9 per metric ton of cement (equivalent of 0.27 metric ton of C or 1 metric ton of CO_2). In other words, instead of installing expensive technologies or switching to less carbon-intensive fuels to reduce CO_2 emissions, the cement industry could pay other entities $6 - $9 for every 1 metric ton of CO_2 they reduce. In essence, the CO2 emissions of the cement industry are negated indirectly through CO_2 reductions from other entities. While this might be an attractive option for some cement plants, the cost of carbon trading can absorb 9 – 13% of the sale price of cement on a per unit mass basis in 1996.

(c) CKD generation

Despite the toxicity and well-documented environmental impacts of CKD (cement kiln dust), it is surprising to find that the documentation of its generation and management lack during literature review. It is suggested, from limited data, that hazardous waste combustion increases the quantity and toxicity of CKD, although it is increasingly being recycled in the kiln (Jacott et al, 2003). Currently, the regulation of CKD management in the U.S. is being delayed until further study of current management practices (Jacott et al, 2003).

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[50] Author's calculations based on EIA 'Emissions of Greenhouse Gases in the United States 1999' data.

[51] From Sandor and Skees (1999), *Magazine of the American Agricultural Economics Association*: Values used by Environmental Financial Products. Estimates could range from $15 per ton (Council of Economic Advisers) to $348 per ton (Energy Information Administration). http://www.envifi.com/Bios/Choices.htm

(d) Production of blended cements

The use of fly ash and other waste materials as SCMs seem promising. Tracking of the replacement rate of cement with SCM and other waste products is highly crucial in address the dynamics between cement and concrete production since a decreasing cement ratio is used[52] (see Chapter 4). A Portland Cement Association analysis showed that it is feasible to produce blended cement equivalent to 36% of the total volume of cement produced in the United States (cited in Hawkins, 2004). Typically, fly ash is used to replace 20% of cement and ASTM Class F fly ash can go up to 60% in particular (Meyer 2002; Malhorta and Ramezanianpour, 1994). Recent work has also shown that chemically self-activated fly ash can replace 100% of the cement (Samadi, 1996 cited in Meyer 2002). However, there are limitations in using fly ash in concrete, e.g. low strength development and quality control, higher porosity and water content requirement.

8.4.3 Off-site production of concrete

Due to its low recycling rate, a major concern associated with this stage is the quantity of wastewater disposed of. For a given mass of total waste produced, the wastewater generated in the United States (26%) is half of that generated in the Netherlands (at least 56%)[53] (Souwerbren, 1996). The huge disparity should be investigated with more surveys to verify the coefficients used in the study[54]. The huge quantity of wastewater disposed of (78% of the total waste *disposed)* suggests untapped potential in reusing wastewater, especially from concrete road construction. Guidelines do exist. As examples is the ASTM C 94, which allows the use of wash out water as mix water if the solids content is less than 5% (50,000 ppm). Moreover, the NRMCA (National Ready-Mixed Concrete Association) is conducting research for the use of wash water of higher solids contents (ENTRUST, 2000). On a positive note, there is already environmental legislation for ready-mixed concrete plants to operate a zero-discharge production process in certain areas in the United States (ENTRUST, 2000).

It is found that the production of precast concrete is 'leaner' and produces only 1/6th solid waste and wastewater compared to ready-mixed concrete on a per volume basis. From a resource conservation perspective, substituting precast concrete for ready-mixed concrete might be an option. Precast concrete also facilitates construction since waiting time for the concrete lower layers to cure is eliminated (AIA ERG, 1996). However, the tradeoff is the versatility of producing non-standard shapes and forms using ready-mixed concrete. In addition, the energy consumed in producing concrete bricks and blocks is double that of ready-mixed concrete, precast concrete and concrete pipes on a per volume basis. Consequently, more energy-efficient curing kilns for concrete brick and blocks production could be explored.

8.4.4 Use of concrete

As seen from the MFA results, the material and energy flows vary among the different concrete types. Consequently, this study further supports the conclusion made by Vares and Häkkinen (1998) that the impacts of concrete production are more dependent on

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[52] See Chapter 4.3.

[53] 11 ready-mixed and concrete products in the Netherlands were surveyed.

[54] Wastewater coefficients for this study mainly comes from the PCA LCI of Portland Concrete.

product choice and concrete design. For example, this study shows that the placing of ready-mixed concrete uses the most energy and water compared to the assembly of concrete products. Cole (1999) came to the similar conclusion that cast-in-place structural assemblies (i.e. placing of ready-mixed concrete) require more construction energy than precast concrete. Product choice and concrete design are key factors of a more responsible materials consumption approach. Comparisons among the three main end-use categories found that road paving consumed the most water and energy and generated the largest mass of solid waste.

Due to the sheer mass of concrete used in buildings, building waste accounts for the largest quantity of the total solid waste during the use phase even though buildings use materials most efficiently. In addition, the building stock accumulated the fastest (96%) in 1996, followed by the other infrastructure stock (93%) and the highways and roads stock (83%). In other words, it takes the road stock 62% longer to double compared to the building stock.

At first glance, buildings appear to be the main consumer of concrete since 57% of the concrete was used in buildings, followed by highways (26%) and other infrastructure (17%). In reality, the use of concrete in residential buildings and highways are comparable when buildings, as a general end-use category, are further broken down into residential, industrial and commercial and public buildings. In decreasing order, the top end-use subcategories are as follows:

1. Residential buildings (31%)
2. Highways and roads (26%)
3. Industrial and commercial buildings (18%)
4. Other infrastructure (17%)
5. Public buildings (8%)

The large demand for building materials in residential buildings is not attributed to significant population increase in the United States. In fact, the trend is propelled by an increase in average size of new home per capita[55] (National Association of Home Builders, 2004 cited in Fox, 2005) and an increase in second-home ownership[56] (National Association of Realtors, 2004 cited in Fox, 2005). Furthermore, 80% of the newly-constructed residential buildings are single family housing[57] (PCA Apparent Use Summary, 1998). There are serious repercussions on resource and energy drains from building more single-family housing of increasing area per capita—only to be partially occupied throughout the year. Some consequences include the creation of a huge redundant building stock of concrete waiting to be disposed of in 20 – 50 years, additional transportation costs imposed by placing and/or assembling more concrete and the increase in induced demand for amenities and other infrastructure.

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[55] Since 1950, the average new house has increased by 1,247 square feet while the average household size has decreased by 1 person.

[56] Since 2001, there is a 24% increase in the number of Americans with second homes.

[57] The remaining 20% consists of multi-family housing, hotels and motels.

8.4.5 Waste management of concrete

Since demolition waste contributes a significant amount of waste solid, more recycling efforts focused on the demolition of buildings, other infrastructure, and in particular highways and roads is optimal. Though buildings consume 54% of the total concrete poured, they also use the least amount of recycled concrete aggregates (estimated 6-7% of waste concrete recycled). Limited applications for waste concrete in buildings due to quality control may be a key factor. Nevertheless, a small concrete recycling rate in the building stock is not necessary a negative trend, because it is currently more efficient and cheaper to reuse/recycle waste aggregates with minimal processing as in subbase applications.

8.5 Conclusions

The overview of the MFA results for the entire life cycle of concrete is presented qualitatively and graphically. To increase the reader's understanding of the mass flows in the physical sense, a Sankey diagram and a per capita materials consumption diagram are used. In addition, diagrams of mass, energy and CO_2 flows showing transportation as a separate stage are used to increase the ease of comparison with other literature. Key flows are also identified and ranked.

Next, various mass and energy flows and embodied energy are compared with other literature to validate the current study. While available data on hidden flows and C&D waste mass flows are too aggregated for direct comparison, they are useful for the comparison as physical limits. In addition, the percentage distribution of energy flows along the life cycle of concrete is verified to be similar to that of a key data source. A slight discrepancy in the embodied energy of aggregates and cement is found when compared with a Norwegian study and a Portland Cement Association study respectively. Differences in system boundaries and quality of data sources may be key factors. Nevertheless, the embodied energy of ready-mixed concrete is found to be within range when compared with three different sources. Similarly, the CO_2 emissions per unit mass of concrete are also found to be comparable with others.

Last but not least, some of the current and potential material management opportunities are discussed in details for each life cycle stage of concrete. Similar to other industries, the cement and concrete industries have tapped into material management opportunities, which increase the bottom line of the industries (e.g. improving energy efficiency of cement manufacturing, and minimal cement wastages and solid waste incurred during concrete production). It is implied that economic incentives and disincentives can direct the industry to more efficient materials management strategies. However, inherent constraints of internalizing environmental costs in the current monetary economy limit the soundness of such economic instruments. The demand-side management approach is recommended as a more optimal approach to recycling by increasing the materials effectiveness of concrete. In addition, the author identified untapped opportunities in minimizing water consumption during the extraction and off-site production stages. Moreover, three key observations are made: (i) the energy efficiency of the cement industry in the United States is close to saturation, (ii) product choice and concrete design are dominant factors of a more responsible materials consumption approach, and (iii) the current trend of building more and larger single-family housing in the United States, only to be partially occupied, pose serious repercussions on resource and energy drains in the foreseeable future.

CHAPTER 9 FUTURE WORK

9.1 Summary

This thesis has produced a material flow analysis of concrete in the United States in 1996 to identify opportunities for more effective materials management. The three main contributions of the research are:

(1) Defining the lifecycle of concrete from the extraction of raw materials stage to waste management stage;
(2) Identifying the dominant concrete products and end-use categories during the use of concrete and the end-uses of recycled concrete; and
(3) Performing a comprehensive set of associated material, water, energy and emissions flows for the lifecycle of concrete

Firstly, the lifecycle of concrete has been successfully delineated into the following five stages. The value added to the understanding of how the United States produces and consume concretes lies in the distinction between off-site production and on-site production of concrete. Most studies typically focus on off-site production of ready-mixed concrete and concrete products and do not relate the parallel movement of on-site concrete production. Subsequently, a comprehensive lifecycle which covers the following:

(i) Extraction of raw materials
[Total materials moved or lithosphere material → Useable raw materials]
(ii) Manufacturing of cement
[Cement raw materials → Cement]
(iii) Off-site production of concrete
[Concrete raw materials, cement and water → Ready-mixed concrete (general and road mixes) and concrete products]
(iv) Use of concrete
[On-site production: Concrete raw materials, cement and water → Building materials, mortar and other infrastructure concrete; Allocation of concrete among end-use categories]
(v) Waste management of concrete
[Construction and renovation waste and demolition waste → Landfill and recycled concrete aggregates]

Secondly, eight dominant concrete types in the United States are identified, namely ready-mixed concrete (general mix and road mix), concrete products (bricks or blocks, precast concrete and concrete pipes), building materials, mortar and other infrastructure concrete. The concrete produced is then further allocated among three end-use categories—buildings, highways and roads and other infrastructure. Furthermore, it is found that the main end-uses of recycled concrete are new cement concrete, new bituminous concrete, subbase, general fill, rip rap and other.

Thirdly, four types of associated mass flows (material, water, energy and emissions) were examined for each of the lifecycle stages of concrete.

9.2 Conclusions

The main conclusions of this research are as follows, for the year 1996:

11. Based on the apparent consumption of 90 Mt of cement, 800 Mt of concrete was *consumed* in the physical infrastructure of the United States. Altogether, the *production* of the 90 Mt of cement and 868 Mt of concrete required **478 Mt water, 100 Mt recycled aggregates, 96 Mt of cement and SCM and 919 Mt of total materials moved** for 725 Mt useable raw materials.[58]
12. The overall efficiency of producing concrete is estimated to be **65%**. Alternatively, the waste production rate is 35%. Most of the waste is made up of wastewater (44%), followed by mining waste (38%) and concrete production solid waste (18%).
13. The extraction of cement and concrete raw materials produced the largest mass flows in the life cycle of concrete. For every metric ton of raw materials, 1.3 metric ton of total materials were moved. Altogether, this stage accounts for **18% of the total minerals, mining overburden and waste produced in the United States** in 1996. In addition, this stage consumed the most water in absolute values.
14. Cement manufacturing emitted the **most CO_2** (51% of total), equivalent to the sum of CO_2 emitted from the other four stages. The same also applies for **energy** consumption (51% of total).
15. It is estimated that **145 Mt of CO_2** was emitted for the entire life cycle of concrete in the United States in 1996. This is double that of CO_2 emitted from cement manufacturing as estimated from various sources. In other words, concrete production accounted for **6% of total CO_2** emissions produced from the energy and industrial sectors in the United States in 1996.[59]
16. More than three-quarters of cement was made into **ready-mixed concrete (67% of total consumed) and concrete products (11%)** in off-site concrete plants. This stage is the second largest water consumer, with wastewater making up 78% of the total waste *disposed.*
17. Among the concrete types, the batching, mixing and placing of **ready-mixed concrete consumes the most energy and water** (up to six times more than precast concrete on a per volume basis).
18. Concrete is mainly consumed **in buildings (57%), followed by highways and roads (26%) and other infrastructure (17%).** The allocation of concrete among building types is **54% for residential, 32% industrial and commercial and 14% public buildings.**

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[58] The production of 800 Mt concrete required 273 Mt water, 100 Mt recycled aggregates, 96 Mt of cement and SCM and 771 Mt total materials moved. For the domestic production of 79 Mt cement, 149 Mt total materials were moved and 205 Mt water and 1.3 Mt of SCM were consumed.

[59] Total U.S. CO_2 emissions from energy and industry in 1996 was 1,484.1 MtC or 5,440 Mt CO_2. However, it is likely that CO_2 from transportation is not included.

19. In 1996, the building stock accumulated the fastest (96%), followed by other infrastructure (93%), then highways and roads (83%). In other words, it takes the road stock 43% longer to double compared to the building stock.
20. Among the end-use categories, **road concrete paving is the major resource consumer.** It used 2.5 times more water than general ready-mixed concrete during off-site production. During the use stage of concrete, road concrete paving consumes up to 50% of the total energy and produces the most waste (55%).
21. Though building construction generates the least amount of waste (at 4% of input concrete), it produces the second highest quantity of waste (30%) in total due to its sheer mass (54% of total mass).
22. Up to six times **more waste concrete was recycled internally** during off-site production of concrete than the recycling of construction and demolition waste concrete.
23. The total transportation energy can be as high as 14% of the total energy consumption during the life cycle of concrete.

9.3 Future work

Three main areas of future work are identified:

1) *To fill in data gaps and update assumptions.*

The most significant gaps are:

Extraction of raw materials	- Quantity and end-uses of water (including embodied water retained in the raw materials) - Transportation of raw materials to concrete plants versus to job site directly
Manufacturing of cement	- Transportation energy of fly ash to cement plants - Quantities and end uses of fly ash in cement plants
Production of concrete	- Transportation energy of fly ash to concrete plants (for comparison to that of cement) - Quantities and end uses of fly ash in cement plants
Use of concrete	- Allocation among buildings, highways and roads and other infrastructure - On-site solid waste production of placing ready-mixed concrete, on-site production and assembly of concrete products. - Additions to physical infrastructure stock
Waste management	- Breakdown of C&D waste by roads and by other infrastructure - Energy consumption for demolition, landfilling, recycling and transportation.

2) *To expand on the current MFA*

Mass balances can be performed on oxygen (oxygen versus used oxygen) and/or fuel consumption. With the inclusion of oxygen, the mass of concrete produced will increase slightly.

3) *To determine the actual stocks of physical infrastructure*

The interest in determining building and other physical infrastructure stocks is growing, particularly in the developed countries. This is due to changes in building demand from new construction to maintenance and refurbishment; the relevance of building stock to national energy policies; building waste; domestic mass flows; resource reserves; and for predicting building demand (Kohler and Hassler, 2002). In addition, knowing the building stock characteristics is crucial for assessing acid rain damage, heat island gains and urban morphology (Ellefsen, 1991). The use of readily available housing stock indicators is often limited in grasping the actual volume of construction due to issues such as overstating of permit valuations; or building permits not reflecting actual completed construction projects. Examples include volume of construction (contracts awarded and building permits); construction finances (bond flotations); construction costs (material cost indexes); and vacancy and occupancy surveys. Researchers have also used Sanborn maps, tax assessments, input-output tables, and buildings mapping (Ellefsen, 1991). Alternatively, additions to stock could be estimated using MFAs, as demonstrated in Chapter 6. A more extensive database of time-dependent variables, particularly the mass flows entering and leaving the physical infrastructure stock, is required.

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APPENDICES

APPENDIX A: 'Extraction of raw materials'

A(c) Energy

For extraction of cement raw materials:

Two computation approaches (based on per ton cement and per ton raw material) are used.

Table A 1 Total energy use coefficients for cement raw materials (based on per ton cement)

	Quarrying/processing (GJ/ton cement)	Transportation (GJ/ton cement)
PCA, LCI of Portland cement	0.080	0.017
ATHENA	0.0442	0.08003
Check: Buzzi Unicem	0.865	0.150

- PCA LCI of Portland cement gives 0.017 GJ/ton cement for transportation of purchased materials. Transportation for quarried materials is included in the quarrying/processing stage.
- Buzzi Unicem: includes electricity.
- Check: Vold & Rønning (1995): quarrying/processing energy = 0.044 GJ/t.

Table A 2 Total energy use coefficients for cement raw materials (based on per ton raw material) – AIA ERG (1996)

	Mass (Mt)	Quarrying/ processing (GJ/ton raw material)	Total quarrying energy (PJ)	Transportation (GJ/ton raw material)	Total transportation energy (PJ)
Sand & gravel	2.15	0.500	1.1	?	?
Limestone & cement rock (estimate 1)	106	7.43	785.8	77% by truck; <100 miles (roundtrip)	n/a
Limestone & cement rock (estimate 2)		0.191	20.2	0.582	61.5
Gypsum	4.13	3.26	13.5	U	-
Clay & shale	8.95	n/a	n/a	n/a	n/a
Iron ore (estimate 1)	1.54	2.03	3.1	0.58	0.89
Iron ore (estimate 2)		-	Part of 1.5 PJ	-	Part of 1.5 PJ
Total	122	-	**> 36.3**	-	**> 62.4**

U = unquantifiable; n/a = not available

- Quarrying/processing energy for sand and gravel is approximated as that for glass sand mining of 454 MJ/short ton, which is probably an overestimate.
- Limestone (estimate 1): Approximately 0.55 MJ required for mining 1 pound of limestone (Hannon et al 1976 and Brown et al 1985 cited in AIA ERG, 1996). Additional 2.79 MJ expended in crushing, screening, grinding and calcining the limestone to produce quicklime. Total embodied energy for quicklime estimated at 3.37 MJ/lb quicklime ($CaCO_3$).
- Limestone (estimate 2): The energy required for limestone mining and processing is estimated at 0.164 mill Btu/ton (Tellus Institute, 1992 cited in AIA ERG, 1996). A widely-accepted estimate of cost of ore transportation = 0.5 mill Btus/ton.
- Gypsum: Approximately 0.74 – 1.055 MJ required for mining 1 pound of gypsum and additional 0.74 MJ expended in crushing, screening, grinding and calcining to produce 1 lb of calcined gypsum (Brown et al, 1985 cited in AIA ERG, 1996). Embodied energy for materials preparation for calcined gypsum estimated at 1.48 MJ/lb calcined gypsum. Transportation unquantified.
- Iron ore (estimate 1): Ore beneficiation (enrichment) is estimated at 1,846 MJ per (short) ton of enriched ore. The energy consumption associated with mineral mining is difficult to estimate because it varies so greatly with process and location. Cost of ore-transportation is distance-dependent, but a widely-accepted estimate is about 527.5 MJ per (short) ton delivered to the steel mill (AIA ERG MAT 09200).
- Iron ore (estimate 2): Energy required for drilling, blasting, loading and transporting iron ore is estimated to range from 52-110 MJ per (short) ton of rock mined (Chapman, 1983 cited in AIA ERG, 1996).
  Energy required for beneficiation is estimated to be between 230 and 700 MJ per (short) ton of ore.
  At most U.S. Taconite mines, 5 – 6 tons of material must be mined for each ton of usable product. 3 tons of crude ore must be processed for each ton of pellets produced. (AIA ERG 1996 MAT 05410).
  Assuming 5.5 tons mined/ton of usable iron ore,
  1.54 mill t iron ore * 5.5 tons rock mined/ usable iron ore = 8.47 mill t rock mined
  Energy used for mining and transporting = [(52+110)/2] MJ/ short ton rock mined * 1 short ton/ 0.9072 t * 8.47 mill t rock mined = 756.25 mill MJ
  Energy used for beneficiation = [(230 + 700)/2] MJ/ (short) ton ore * 1 short ton/ 0.9072 t * 1.54 mill t iron ore = 789.35 mill MJ
  Total energy used for mining, transporting and processing 1.54 mill t iron ore = (756.25 + 789.35) mill MJ = 1545.6 mill MJ
- Estimated minimum total for quarrying energy = 1.1 + 20.2 + 13.5 + 1.5 = 36.3 PJ
- Estimated minimum total for transportation energy = 61.5 + 0.89 = 62.4 PJ

Table A 3 Total energy use coefficients for cement raw materials (based on per ton raw material) - McEvoy et al (2004)

Raw material	Mass (Mt)	Energy (MJ/t raw material)	Total extraction energy (PJ)
Sand & gravel	2.15	19.06	0.0419
Limestone & cement rock	105.76	44.28	4.682
Gypsum	4.13	19.00	0.0785
Clay & shale	8.95	47.29	0.423
Iron ore	1.54	n/a	n/a
Total			**> 5.2**

For extraction of concrete raw materials:

Two computation approaches (by per ton raw material and by concrete type) are used.

Table A 4 Total energy use coefficients for concrete raw materials (based on per ton raw material) – PCA LCI of Portland concrete & BEES

	Quarrying/processing (GJ/ton raw material)		Transportation (GJ/ton agg km)	Roundtrip distance (km)
	Sand & gravel	Crushed stone		
PCA, LCI of Portland concrete	0.047	0.081	0.00106 (assumes all diesel)	50
BEES (assumes all crushed rock)	0.155		0.00118	80

- BEES assumes method of transport is by truck.
- Note: Mroueh et al 2001: assumes transportation distance of sand and gravel as 50 km and crushed stone as 10 km.

Table A 5 Total energy use coefficients for concrete raw materials (based on per ton raw material) – UK/McEvoy et al (2004)

	Mass (Mt)	Energy (MJ/t raw material)	Total extraction energy (PJ)
Sand & gravel	398	19.06	7.59
Crushed stone*	205	44.28	9.08
Total	**603**	**-**	**16.7**

(Based on McEvoy et al (2004) data.)

*: Since crushed stones are mainly made of limestone, limestone coefficients from McEvoy are used for the extraction energy of crushed stones.

Table A 6 Total energy use coefficients for concrete raw materials (by concrete product)

	Quarrying/processing (GJ/m^3 concrete)		**Transportation (GJ/m^3 concrete)**		**Total concrete (mill m^3)**
	Sand & gravel	**Crushed stone**	**Sand & gravel**	**Crushed stone**	
20 MPa ready mix concrete	0.036	0.098	0.042	0.058	195
30 MPa ready mix concrete	0.036	0.098	0.039	0.061	5.2
35 MPa ready mix concrete	0.034	0.094	0.036	0.061	9.3
Road ready-mixed concrete*	0.030	0.040	0.028	0.054	93
Brick/block	0.066	0.050	0.104	Not applicable	24
50 MPa precast concrete	0.030	0.040	0.028	0.054	2.1
70 MPa precast concrete	0.032	0.086	0.031	0.057	2.4
Architectural precast panels	0.032	0.090	0.038	0.055	2.7
Pipes*	0.034	0.094	0.036	0.061	8.1
Building materials*	0.036	0.098	0.042	0.058	17
Mortar*	0.036	-	0.042	-	13
Other infrastructure*	0.034	0.094	0.036	0.061	15
				Total	**386**

(Coefficients from PCA, LCI of Portland concrete)

*: Coefficients are estimated based on total aggregates in concrete mix: for 'road' – use 50 MPa precast concrete; 'pipes' – use 30 MPa ready-mixed concrete; 'building materials' – use 20 MPa ready-mixed concrete; 'mortar' - use only sand and gravel coefficients of 20 MPa ready-mixed concrete (since mortar mix contains only fine aggregates, which is of a similar quantity as 20 MPa ready-mixed concrete); 'other infrastructure' – use 35 MPa ready-mixed concrete

- The transportation of energy for raw materials for concrete to concrete plant and to the site directly is assumed to be the same. A similar assumption was made by Brocklesby and Davison, 2000.
- Check: Vold & Rønning 1995: extraction energy for aggregates for concrete = 0.084 GJ/m^3 concrete; transportation energy = 0.071 GJ/m^3 concrete.

Table A 7 Total emissions from 'Extraction of raw materials' stage

(Mt)	CO_2	SO_2	NO_X	CH_4	CO	PM	VOC
Processing:							
- cement	16.6	0.0236	0.153	0.00589	0.153	9.98	0.0294
- concrete	21.6	0.0307	0.199	0.00767	0.199	13.0	0.0383
Transport:							
- cement	0.621	0.000900	0.00855	0.000135	0.00315	0.000900	0.000900
- concrete	3.11	0.00450	0.0428	0.000675	0.0158	0.00450	0.00450
Total emissions	**42**	**0.060**	**0.40**	**0.014**	**0.37**	**23**	**0.073**

Table A 8 Emission coefficients for 'Extraction of raw materials' stage

(kg/GJ)	**CO_2**	**SO_2**	**NO_X**	**CH_4**	**CO**	**PM**	**VOC**
Processing	31.3	0.0444	0.289	0.0111	0.289	18.8	0.0556
Transportation	69.1	0.100	0.950	0.0150	0.350	0.100	0.100

- Author normalized coefficients to 1 GJ of energy from PCA LCI of Portland concrete data (estimated based on EPA AP-42 emissions factors).
- Transportation emission coefficients specific for 50% truck diesel, 50% rail diesel.

APPENDIX B: 'Manufacturing of cement'

B (a) Materials

Table B 1 Solid waste (CKD) coefficients of cement manufacturing

	Production (kg/t cement)	Recycled (kg/t cement)	Other uses (kg/t cement)	Disposed (kg/t cement)
PCA, LCI Portland Cement	69.8	17.6	-	52.2
ATHENA	44.0	32.1	-	11.9
Check: Buzzi Unicemen	-	-	2.91	

- AIA: Production refers to the generation of gross CKD (i.e. CKD collected by air pollution control devices). The standard industry practice is to place it in piles, quarries or landfills. "Other uses" refer to off-site use as a waste stabilizer, fertilizer, liming agent or materials additive.
  EPA figure of 12.7 Mt in 1990 also found in: Environmental Fact sheet (1999) http://www.epa.gov/epaoswer/other/ckd/ckd/ckdp-fs.pdf
- ATHENA: This is the average of the figures from the 4 regions. It is assumed that 'Waste CKD' refers to CKD disposed, and subsequently the remainder is recycled.

Notes to fly ash:

In 1996, 1.26 Mt of fly ash was used as a raw material in cement plants: as kiln/raw feed and as admixture/pozzolan for 0.8 Mt of blended cement (van Oss 1996). In addition, Malhotra & Hemmings (1995) indicated that the Dundee Cement Company in Michigan was the only one cement plant in the United States which produces blended cements[60]. Given that the composition of blended cement this company produces is 20% fly ash and 80% Portland cement, it is assumed that 20% of 0.8 Mt (total amount of blended cement produced) or **0.2 Mt fly ash was used as an admixture, while 1.1 Mt was used as kiln/raw feed**. In addition, 7.2 Mt fly ash was used in cement/concrete products in 1996 (Turner Fairbank Highway Research Center/Federal Highway Administration, 2002). Discounting for the 1.3 Mt used in cement manufacturing, the remaining **5.9 Mt fly ash** is estimated to be used in concrete production.

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[60] Currently, at least three more companies have entered the fly ash market: Carolinas Cement, Phoenix Cement and Mineral Solutions Inc (Cement Americas, 1999).

B (b) Water

Table B 2 Water input and output coefficients for the cement manufacturing stage

	Input		Output	
	Slurry water (t/t)	**Process water (t/t cement)**	**H_2O vapor (t/t)**	**Effluent (t/t cement)**
PCA LCI of Portland Cement	0.819 for wet process cement	n/a	0.819 for wet process cement	n/a
AIA ERG	0.8 for wet process clinker	n/a	0.8 for wet process clinker	n/a
ATHENA	-	2.0[a]	1.5	0.5
Van Oss & Padovani 2003	0.8 for wet process clinker	n/a	0.8 for wet process clinker	n/a
Check: Buzzi Unicem	0.095 for cement	0.133[a]	0.195 for cement	0.033

a: Author assumes that 75% of process water is evaporated from cooling kiln exhaust gases and cooling finish mills and 25% exits as effluent from non-contact cooling of bearings.

- 'Slurry water' = water as a raw material and to make slurry for wet-process kilns. 'Process water' = water used in the cement plant for cooling machines and for conditioning exhaust gases from the pyroprocessing kilns.
- PCA LCI of Portland Cement: 0.819 t water/ t of cement for wet process. This water is evaporated.
- AIA: only water used during raw material preparation is for slurry preparation in the wet process, i.e. about 0.8 ton of water per ton of clinker production. This water is vaporized during the burning process in the kilns and not discharged.
- ATHENA: average of process water of 20 MPa and 30 MPa ready-mixed concrete. Author assumes that 75% of the process water is evaporated from cooling kiln exhaust gases and cooling finish mills and 25% exists as an effluent after non-contact cooling of bearings.
- Buzzi Unicem: 229.74 kg water/t cement is used in the cement manufacturing process of which approximately 95 kg water/t cement is consumed as input. The remaining water is used for cooling machines and conditioning exhaust gases from the pyroprocessing kilns. Author makes the same assumption that 75% water is used in evaporative cooling (75% * 0.133 t water/t cement = 0.1 t) and 25% as non-contact cooling (25% * 0.133 t = 0.033 t).

B (c) Energy

To account for the energy used (including electricity) only for the domestic production of clinker (70.4 Mt or 96.7% total clinker used) and cement (79.3 Mt), the energy coefficients are adjusted. By including the production of the imported clinker in the MEFA (though a mere 2.3%), the cement manufacturing energy consumption is likely to be overestimated since the pyroprocessing process is highly energy-intensive. Therefore, the energy required for raw meal preparation and pyroprocessing per unit mass of cement will be reduced by 2.3%. First, the average percentages of energy used per stage is computed as:

Table B 3 Average percentages of energy use in cement manufacturing by stage

	Raw meal preparation (GJ/t cement)	Pyroprocessing (GJ/t cement)	Finish grinding (GJ/t cement)	Total energy used
PCA, LCI of Portland cement	1.6%	93.1%	5.3%	100%
ATHENA	8.6%	87.1%	4.3%	100%
Check: Vold & Rønning 1995	4.8%	90.0%	5.2%	100%
Average percentages	**5.1%**	**90.1%**	**4.8%**	**100%**

Therefore, an adjustment of 2.3% * (5.1% + 90.1%) = 2.19% will be made.

Table B 4 Energy use coefficients for cement manufacturing – including electricity (figures before adjustment are in parenthesis)

	Raw meal prep. (GJ/t cement)	Pyroprocess (GJ/t cement)	Finish grinding (GJ/t cement)	Total (GJ/t cement)	Transp. (GJ/t cement)	Transp. (GJ/t material km)	Round-trip dist. (km)
Van Oss & Pavodiani (2002)	-	-	-	5.36 (5.48)			
PCA, LCI of Portland cement	0.080 (0.082; 1.6%)	4.771 (4.878; 93.1%)	0.270 (0.276; 5.3%)	5.12 (5.236; 100%)	-	-	-
PCA, LCI of Portland concrete	-	-	-	See table below	-	0.00106 (assumes all diesel)	100 (for cement & fly ash)
BEES	-	-	-	5.203 (5.320)	-	0.00118	97 (for cement & fly ash)
AIA ERG, 1996; Hannon et al (1976)	-	-	-	-	0.344	-	-
ATHENA	0.386 (0.395; 8.6%)	3.897 (3.984; 87.1%)	0.191 (0.195; 4.3%)	4.472 (4.573; 100%)	0.330	-	-

- AIA ERG: for hauling cement to job site. It gives embodied energy of Portland cement as 5.585 MJ/kg (Portland Cement Association 1994) but does not break it down to raw material extraction, cement manufacturing and transportation.
- PCA, LCI of Portland cement: Energy for raw material preparation is taken to be the sum of energy used for recovery of materials from stockpiles, proportioning to the correct chemical composition, grinding and blending to raw meal.
  The energy use percentage for the pyroprocessing stage is rounded down by 0.1% as the rounding up process would cause a slight discrepancy.
- PCA, LCI of Portland concrete: The total energy used for cement manufacturing (GJ/ t cement) is weighted using PCA, LCI of Portland concrete coefficients by product. Transportation energy is from source of material to the concrete plant.
- ATHENA: Energy for raw material preparation is taken to be the sum of energy used as that for primary crushing, secondary crushing and raw grinding. Transportation is taken as the average of the 4 regions.
- Buzzi Unicem: 3.869 GJ/t cement (includes electricity).
- Mroueh at al 2001: assumes transportation distance for cement 100 km, fly ash 10 km, blast furnace slag 50 km (Finland).

Table B 5 Energy use coefficients for cement manufacturing by product (PCA LCI of Portland Concrete)

	20 MPa ready mix	30 MPa ready mix	35 MPa ready mix	Bricks/ block	50 MPa precast	70 MPa precast	Arch. precast	Mortar	Roads	Other infrast.
Energy used (GJ/m^3 concrete)	1.18	1.48	1.78	1.10	2.68	2.36	2.05	1.57	1.18	1.78
Volume (mill m^3)	255.4	9.1	11.3	27.3	2.8	3.2	3.7	8.1	27.0	13.5
Subtotal energy (PJ)	301.4	13.5	20.1	30.0	7.5	7.6	7.6	12.7	31.9	24.0
Total (PJ) – before adjustment	456.2									
Total (PJ)	**446.2**									

- Roads: cement manufacturing energy assumed similar to 20 MPa ready mix.
- Mortar: cement manufacturing energy as average of ATHENA data for the 4 Canadian areas.

Using the average percentages of energy used for raw meal preparation, pyroprocessing and finish grinding, the total energy used per stage is computed as:

Table B 6 Average percentages of energy use in cement manufacturing by stage

	Raw meal preparation (GJ/t cement)	Pyroprocessing (GJ/t cement)	Finish grinding (GJ/t cement)
PCA, LCI of Portland cement	1.6%	93.1%	5.3%
ATHENA	8.6%	87.1%	4.3%
Check: Vold & Rønning, 1995	4.8%	90.0%	5.2%
Average percentages	**5.1%**	**90.1%**	**4.8%**
Subtotal energy use (PJ)	**19.5**	**344.4**	**18.3**
Total energy use (PJ)	**382.2**		

- Vold & Rønning, 1995: Nordic countries (Finland, Sweden and Norway).

B (d) Fuel

- To convert energy to MMTOE (million metric tons of oil equivalent): 41.868 PJ = 1 MMTOE

B (e) Emissions

Table B 7 Total emissions from 'Manufacturing of cement'

(Mt)	**CO_2**	**SO_2**	**NO_X**	**CH_4**	**CO**	**PM**	**VOC**
Process:							
- Calcination & fuel combustion	72	0.16	0.20	0.0027	0.068	0.02	0.0028
- Total cement manufacturing*	72	0.16	0.21	0.0028	0.070	0.20	0.0032
Transportation	0.62	0.0011	0.0085	0.00011	0.0032	0.0011	0.00053
Total	**72.9**	**0.16**	**0.21**	**0.0029**	**0.073**	**0.20**	**0.0037**

Table B 8 Emission coefficients for 'Manufacturing of cement'

(kg/GJ)	**CO_2**	**SO_2**	**NO_X**	**CH_4**	**CO**	**PM**	**VOC**
Process:							
- Calcination & fuel combustion	182	0.399	0.515	0.00692	0.171	0.0435	0.00712
- Total cement manufacturing*	170	0.373	0.485	0.00659	0.165	0.474	0.00758
Transportation	69.3	0.118	0.941	0.0118	0.353	0.118	0.0588

*: Includes raw meal preparation, calcination, fuel combustion & finish grinding.

(Based on the fuel mix given in the PCA LCI of Portland concrete, which is pretty similar to the fuel mix defined in Figure 4.3. The PCA fuel mix has a lower coal content and higher pet coke and natural gas.)

- Author normalized coefficients to 1 GJ of energy from the weighted average emission coefficients in the PCA LCI of Portland concrete (estimated based on EPA AP-42 emissions factors). Next, the coefficients are adjusted down by 1% so that the CO2 produced from calcination and fuel combustion tallies with that found in Chapter 4 (c) (72.0 PJ).
- Transportation emission coefficients specific for 50% truck diesel, 50% rail diesel.

APPENDIX C: 'Off-site production of concrete'

C (a) Materials

Table C 1 Solid waste coefficients for off-site concrete mixing/prefabrication (PCA LCI of Portland Concrete 1998, ATHENA)

Solid waste (kg/m^3 of concrete)	**Ready-mixed concrete**[*]	**Bricks/ blocks**	**Precast concrete**	**Concrete pipes**
Estimate 1				
Returned concrete	126	-	-	-
Truck washout	27	-	-	-
Mixer washout	4	-	-	-
Subtotal	157	-	-	-
Recycling	141 (90%)	57.0 (95%)	57.0 (95%)	57.0[a] (95%)
Total waste (estimate 1)	**16**	**3.0**	**3.0**	**3.0**[*]
Estimate 2				
Total waste (estimate 2)	**48.46** (20 MPa)	**1.52**	**1.78**	**1.78**[b]
	48.35 (30 MPa)			
	49.01 (35 MPa)			
Current study estimates	**51** (based on mass balance using on-site & concrete products estimates)	**4.7** (assume 5% wastage by mass)		

[a]: Assume road paving produce similar solid waste quantities and type as (general) ready-mixed concrete.

[b]: Assume data for pipes similar to that of precast concrete.

- Total waste (estimate 1) is from PCA LCI of Portland Concrete.
- Total waste (estimate 2) is from ATHENA.
  - assume total waste for 35 MPa ready-mixed concrete is similar to that of 60 MPa as listed in ATHENA.
  - ATHENA gives solid waste of 0.025 kg/block, i.e. for a typical 0.20 x 0.20 x 0.41 m block, 1.52 kg solid waste/m^3 concrete is produced.
  - assume total waste for precast concrete is similar to that of hollow deck (also made of precast concrete). ATHENA gives 0.440 kg/m (for 4' width, 8" thickness). Converting the solid waste per unit volume gives 0.440 kg / (1 m x 4' x 8") = 0.440 kg/ 0.2477 m^3 = 1.78 kg solid waste/ m^3 concrete.
  - assume total waste for pipes is similar to that of precast concrete is since pipes are a form of precast concrete.

C (b) Water

Table C 2 Water use coefficients for off-site production of concrete

Reference	Type	Input (kg/m^3 concrete)			Output (kg/m^3 concrete)				
		Mix water	**Process water**	**Total influent**	**Truck wash off**	**Truck/ equip. wash out**	**Miscellaneous**	**Total effluent**	**Embodied water**
PCA, LCI of Portland concrete	Ready-mix (general)	141	170^{a} (35 –515)	311	102^{b} (15 – 317)	23^{b} (5 – 69)	45^{b} (15 – 129)	170	141
	Brick/block	142	44	186	-	-	44	44	142
	50 MPa precast	178	85	263	-	85		85	178
	70 MPa precast	136	85	221	-	85		85	136
	Arch. precast	154	85	239	-	85		85	154
	Pipes	109	85	194	-	85		85	198
ATHENA	Ready-mix (general)	160	50	210	50			50	160
	Brick/block	53	12.5	65.5	-	-	12.5	12.5	53
	Precast	202	12.5	214.5	-	12.5		12.5	202
	Pipes	202	12.5	214.5	-	12.5		12.5	202
Jeuffroy et al 1996	Highways & roads	100	176	276	176	176		100	-
Gambatese & Wood, 2002[61]	Highways & roads	395^{c}	-	395	-			-	395

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[61] Reference: ASHTO 1974. From personal communication in May 2005.

'Mix water' = concrete mix water, 'Process water' = water for cooling machines and conditioning exhaust gases, 'Embodied water' = water used for cement hydration to form cement binder for concrete.

- [a]: PCA LCI of Portland concrete uses 170 kg/m^3 concrete as the best estimate.
- [b]: Author's calculations: the averages of the range (166 kg/m^3 for truck wash off, 37 kg/m^3 for truck/equipment wash out and 72 kg/m^3 for miscellaneous uses) are weighed and scaled to 170 kg/m^3 accordingly.
- PCA LCI of Portland concrete assumptions:
  Ready-mix concrete: 170 kg/m^3 concrete is used as a representative quantity until better data can be obtained. This value depends on the type of plant (transport of wet products in trucks require less wash off water than dry products), plant location (rural plants more likely to use transit mixers for the longer haul to job sites) and plant size (larger plants tend to have water-recycling systems).
  Brick/block: Since brick/block operations do not require truck washoffs and washouts, it is assumed that block plants consume 25% of the water used in ready-mix plants.
  Precast: No water is needed for truck wash off since precast concrete is placed in forms at the precast plant instead of loaded in trucks for shipment. Washout of equipment used to transfer concrete to molds and the mixer probably requires similar amounts of water as used in a ready-mixed concrete plant to wash out the mixer and concrete trucks. Therefore, it is assumed that precast concrete consumes 50% of the water used per unit of ready-mixed concrete.
  Pipes: Author's assumption that the water use is equivalent to that of precast concrete since pipes is a type of precast product.
- ATHENA: Water use of precast concrete and pipes are assumed to be similar to double T beams and hollow decks (precast products).

C (d) Fuel

Table C 3 Energy source coefficients for off-site production of concrete (PCA LCI of Portland Concrete)

	Diesel fuel (GJ/m^3)	**Natural gas** (GJ/m^3)	**Electricity** (GJ/m^3)	**Total** (GJ/m^3)
Ready-mixed	0.191	0.042	0.014	0.247
Brick/block	0.225	0.076	0.014	0.315
Precast concrete & pipes	0.191	0.042	0.014	0.247
Average %	**75%**	**19%**	**5.3%**	**100%**

C(e) Emissions

Table C 4 Processing emissions from 'Off-site production of concrete' stage

(Mt)	**CO_2**	**SO_2**	**NO_X**	**CH_4**	**CO**	**PM**	**VOC**
Ready-mixed	4.2	0.025	0.0042	n/a	0.0012	0.030	0.000090
Brick/block	0.75	0.0041	0.00075	0.0000042	0.00021	0.0042	0.000017
Precast	0.10	0.00060	0.00010	n/a	0.000029	0.00073	0.0000022
Pipes	0.12	0.00067	0.00011	n/a	0.000032	0.00082	0.0000024
Total	**5.2**	**0.030**	**0.0051**	**0.0000042**	**0.0015**	**0.036**	**0.00011**

Table C 5 Transportation emissions from 'Off-site production of concrete' stage

(Mt)	**CO_2**	**SO_2**	**NO_X**	**CH_4**	**CO**	**PM**	**VOC**
Ready-mixed	15	0.025	0.14	0.0050	0.14	0.020	0.025
Brick/block	2.5	0.0041	0.024	0.00082	0.023	0.0033	0.0041
Precast	0.74	0.0012	0.0069	0.00024	0.0068	0.00096	0.0012
Pipes	0.84	0.0014	0.0078	0.00027	0.0077	0.0011	0.0014
Total	**19.5**	**0.032**	**0.18**	**0.0063**	**0.18**	**0.025**	**0.032**

Table C 6 Processing emissions factors for concrete plant operations

(kg/m^3 GJ)	**CO_2**	**SO_2**	**NO_X**	**CH_4**	**CO**	**PM**	**VOC**
Ready-mixed	57.49	0.3360	0.05668	n/a	0.01619	0.4089	0.001215
Brick/block	57.45	0.3121	0.05732	0.0003185	0.01592	0.3217	0.001274
Precast	57.49	0.3360	0.05668	n/a	0.01619	0.4089	0.001215
Pipes	57.49	0.3360	0.05668	n/a	0.01619	0.4089	0.001215

- Author normalized to 1 GJ of energy from PCA LCI of Portland concrete data (estimated based on EPA AP-42 emissions factors).
- Specific for 19% natural gas, 5% electricity, 75% diesel.

Table C 7 Transportation emissions factors for diesel fuel

(kg/m^3)	**CO_2**	**SO_2**	**NO_X**	**CH_4**	**CO**	**PM**	**VOC**
Diesel fuel	71.0	0.115	0.656	0.0230	0.649	0.0916	0.115

APPENDIX D: 'USE OF CONCRETE'

Section 6.3.2: 'On-site production of concrete'

D(a) Materials

Table D 1 Solid waste coefficients for on-site production (mixing and placement)

Solid waste (kg/m^3 of concrete)	**Building materials**	**Mortar**	**Other infrast.**	**Ready-mixed concrete**	**Concrete products**
Estimate 1 (Author's assumptions based on PCA LCI of Portland Concrete coefficients)					
Returned concrete	-	-	126	-	-
Mixer washout	-	-	4	-	-
Equipment washout	-	-	27	-	-
Subtotal	-	-	157	-	-
Recycling	-	-	141 (90%)	-	-
Total waste	**3% by mass**	-	**16**	-	-
Estimate 2 (ATHENA)					
Total waste	-	**2.59**	**49.01**	-	-
Estimate 3 (via assumptions and mass balance)					
Total waste	-	-	-	= Total waste 71 Mt (Back calculated from Chap 7) – solid waste from on-site production & concrete pdts; Appropriated by mass balance of concrete products by end-use category.	Assume 5% (slightly larger than 3% wastage during production.)

- For building materials, it is assumed that the solid waste produced through screeding, mixing, etc. is 3% of production (by mass) – about average of 2-5% concrete industry average for solid waste from PCA LCI of Portland Concrete. It is assumed that there is minimal recycling of concrete as building materials because of small scale of the projects which occur sporadically – as opposed to a contractor which could recycle the concrete in other on-going projects.
- For mortar: AIA ERG allows for 15% waste (or equivalent to 2.3 Mt solid waste, MAT 04220 pp. 28), which is considered too high as compared with ATHENA's 2.59 kg/m^3 concrete and is therefore not included.
- For other infrastructure: since the use of concrete is similar to that of ready-mixed concrete (i.e. mixing, placement of concrete and curing), it is assumed that they have similar types and magnitudes of wastages, including the washout of equipment, e.g. pumps and cranes (in substitution of trucks for ready-mixed concrete production).

D(b) Water

Table D 2 Water use coefficients for 'On-site production of concrete' stage

	Type	Input (kg/m³ concrete)			Output(kg/m³ concrete)			
		Mix water	Process water	Total influent	Equipment wash out	Miscell-aneous	Total effluent	Embodied water
PCA, LCI of Portland concrete	Building materials[a]	141	68	209	23	45	68	141
	Other infrast.[b]	141	68	209	23	45	68	141
ATHENA	Building materials[c]	160	20	180	20		20	160
	Mortar	185	25	210	25		25	185
	Other infrast.[d]	165	20	185	20		20	165
Jeuffroy et al 1996	Highways & roads	100	176	276	176		176	100
Current study/ average	**Building materials**	**141**	**44**	**185**	**15**	**29**	**44**	**141**
	Mortar	**183**	**25**	**210**	**25**		**25**	**185**
	Other infrast.	**141**	**44**	**185**	**15**	**29**	**44**	**141**
	General mix	n/a	**170**[e]	**170**	**170**		**170**	n/a
	Highways & roads	n/a	**176**	**176**	**176**		**176**	n/a

''Mix water' = concrete mix water, 'Process water' = water for washing pumps, cranes, forms and tools, sawing, exposing aggregate surface and washing of concrete roads, *'Embodied water' = water used for cement hydration to form cement binder for concrete.*

a: Assume that 'Building materials' require similar amounts of process water as 'Ready-mixed concrete' for washout of equipment and mixer, excluding truck wash off. This is approximated as 68 kg water/m³ concrete.

b: Assume that 'Other infrastructure' requires mix water and 40% process water similar to PCA LCI of Portland Concrete data for '35 MPa ready-mixed concrete' for washout of equipment and mixer, excluding truck wash off.

c: Author assumes that 'Building materials' require 40% (same percentage used for assumption in (a)) of water input as ATHENA's 'Ready-mixed concrete' process water for washout of equipment and mixer – to factor out truck wash off water.

d: Author assumes that 'Other infrastructure' require 40% process water for ATHENA's 60 MPa ready-mixed concrete data (same percentage used for assumption in (a)) for washout of equipment and mixer – to factor out truck wash off water.

e: Assume that placing of ready-mixed concrete (general mix) requires similar water used in concrete plant operations (coefficients from PCA LCI of Portland Concrete).

- Jeuffroy et al 1996: For 0.25 m³ concrete, 4 L water input for sawing, 10 L for exposed aggregate surface and 30 L for washing.

D(e) Emissions

Table D 3 Emissions from 'Off-site production of concrete' stage by subprocess

(Mt)	CO_2	SO_2	NO_X	CH_4	CO	PM	VOC
On-site production							
Mortar - batching	0.0036	0.0000057	0.000033	0.0000011	0.000033	0.0000046	0.0000057
Other infrast. - subtotal	0.027	0.000042	0.00025	0.0000085	0.00024	0.000034	0.000042
- batching	0.013	0.000020	0.00012	0.0000041	0.00012	0.000016	0.000020
- placing	0.014	0.000022	0.00013	0.0000044	0.00012	0.000018	0.000022
Placing of ready-mixed concrete							
General	0.19	0.00031	0.0018	0.000062	0.0018	0.00025	0.00031
Roads	0.085	0.00014	0.00079	0.000028	0.00078	0.00011	0.00014
Assembly of products							
Precast & pipes	0.22	0.00035	0.0020	0.000069	0.0020	0.00028	0.00035
Total	**0.52**	**0.00084**	**0.0048**	**0.00017**	**0.0048**	**0.00068**	**0.00084**

- Emissions from building materials are assumed negligible.

Table D 4 Emissions factors for on-site production operations

(kg/m^3 GJ)	CO_2	SO_2	NO_X	CH_4	CO	PM	VOC
Diesel fuel	71.0	0.115	0.656	0.0230	0.649	0.0916	0.115

- Normalized to 1 GJ of energy from PCA LCI of Portland concrete data (estimated based on EPA AP-42 emissions factors).
- Assume 100% diesel.

D(f) Allocation of concrete

Table D 5 Breakdown of cement use by end-use category (USGS MCS 1996, PCA 1998, Kelly 1998)

	Buildings	Highways & roads	Other infrastructure
USGS (for 1996)[a]	-	4.0%	-
PCA (for 1998)[b]	57.0%	26.4%	16.6%
Kelly (for 1996)[c]	57.7%	38.9%	2.7%

[a] Likely to be understated since USGS indicates that road-paving has also been appropriated in the "Government" and "Ready-mixed concrete" category.

[b] Aggregated by author. 'Other infrastructure' includes farm construction, water/waste management, utilities and other public works, oil & gas well mining and miscellaneous.

[c] Author adjusted Kelly's figures to include 2.7% for non-construction uses which Kelly initially excluded.

Table D 6 Percentage breakdown of cement use by concrete type

Ready mix	Concrete products	Building materials	Mortar	Roads	Other infrastructure	Total
67%	11%	3.8%	4.0%[a]	4.0%[b]	11%[c]	100%

[a] It is also assumed that masonry cement is used in mortar exclusively.

[b] Likely to be understated since USGS indicates that road-paving has also been appropriated in the "Government" and "Ready-mixed concrete" category.

[c] Includes oil well drilling, mining, waste stabilization, soil cement and others.

- May not add up to total due to independent rounding.
- Based on USGS Cement MCS 1996: It gives breakdown by product for Portland cement, which makes up 96% of the total cement output. Hence, this breakdown is adjusted accordingly for the total cement output.

Notes for Table 6.6: Iteration process

1. Known:
    a. 3.8% 'building materials' and 4.0% mortar in 'Buildings'
    b. 26.4% 'ready-mixed concrete' in 'Highways and roads' (since it is a typical procedure.)
2. Assume 1/3 of 'Other infrastructure' comes from ready-mixed concrete, precast concrete (concrete products) and on-site production.
3. Assume that the distribution of 11% as concrete products holds more certainty that the estimate for ready-mixed concrete, and subtracting 5.5% for 'Other infrastructure', it is computed that 5.5% of concrete products is used in 'Buildings.'
4. Lastly, since ready-mixed concrete used in all three end-use categories has to sum to a total of 75.7%, 43.8% is estimated for use in buildings.

Notes for Table 6.10: Estimated breakdown of cement use by type of concrete mix

A) Ready-mixed concrete

90% ready-mixed concrete in 20 MPa range, 8% is 30-35 MPa, only 1-2% higher strengths. (PCA, LCI of Portland Concrete). The author assumes that this accounts for non-road mix uses only. To increase consistency of the MEFA, the ready-mixed concrete will be allocated among 20, 30 and 35 MPa only to facilitate use of the PCA LCI of Portland Concrete coefficients. Therefore, it is assumed that 3% of ready-mixed concrete is of 30 MPa and 7% 35 MPa (to account for 7% of non-road mix ready-mixed concrete used in 'Other infrastructure'.)

Assume for 'Ready-mixed concrete' (**76%** of total cement consumption)

20 MPa ready-mixed concrete	**68% of total cement consumed**
30 MPa ready-mixed concrete	**2.7%**
35 MPa ready-mixed concrete	**4.0%**

Table D 7 Raw materials of concrete by type of ready-mixed concrete (PCA LCI Portland Concrete 2002)

Raw materials of concrete (kg/m^3)	**20 MPa ready-mix**	**30 MPa ready-mix**	**35 MPa ready-mix**
Cement[a]	206	258	335
Water	141	141	141
Fine aggregate	830	770	710
Coarse aggregate	1,100	1,200	1,200
SCM/fly ash[b]	17	21	-
Unit weight	**2,294**	**2,390**	**2,386**

[a] Modified from PCA LCI of Portland Concrete to reflect use of SCMs (in particular fly ash).

[b] Based on 0.0752 kg fly ash/kg cement used in concrete production, as computed in Section 5.2.4

B) Concrete products

USGS indicates that concrete products = 1.655 Mt *brick/block* (18% concrete products); 1.138 Mt *precast* (12%); 0.750 Mt *pipe* (8%); 5.814 Mt *others* (mixture of 3) (62%). Author assumes that the composition for *other* is similar to that of brick/block, precast and pipes.

Table D 8 Estimated percentage of concrete products by type (Author's calculations based on USGS Cement MYB 1996)

	Brick/block	Precast concrete	Pipes
Estimated % of concrete products	47.4	31.6	21.0[*]

[*] *It is assumed that all concrete pipes are used in other infrastructure.*

Precast concrete is equally divided among 50 MPa precast concrete (33.3%), 70 MPa precast concrete (33.3%) and architectural precast panels (33.3%) for a fair sampling of the various precast types available in the PCA LCI of Portland Concrete. The bricks/blocks will be treated as 0.2 x 0.2 x 0.4 m concrete masonry units (CMU) with 50% solid volume for this study.

Assume for 'Concrete products' (**11%** of total cement consumption)

Bricks/blocks	**5.2% of total cement consumed**
50 MPa precast concrete	**1.2%**
70 MPa precast concrete	**1.2%**
Architectural concrete	**1.2%**
Pipes	**2.3%**

Table D 9 Raw materials of concrete by type of concrete products (PCA LCI Portland Concrete 2002, Rinker Materials 1996)

Raw materials of concrete (kg/m^3 concrete)	**Brick/ block**	**50 MPa precast**	**70 MPa precast**	**Arch. precast**	**Pipes**
Cement[a]	194	504	445	386	259
Water	142	178	136	154	109
Fine aggregate	2,033	550	610	740	2014
Coarse aggregate	0	1,100	1,100	1,100	
SCM/fly ash[b]	15	-	-	-	21
Unit weight	**2,383**	**2,332**	**2,347**[c]	**2,380**	**2403**

[a] Modified from PCA LCI of Portland Concrete to reflect use of SCMs (in particular fly ash).

[b] Based on 0.0752 kg fly ash/kg cement used in concrete production, as computed in Section 5.2.4

[c] 70 MPa precast also includes 56 kg silica fumes/m^3 of concrete.

- Raw materials used for concrete pipes are calculated based on minimum cement content of 470 lb/yd^3 concrete, assuming water content ratio of 0.39 (average of listed range of 0.33 – 0.45), and density of 2,402.8 kg/m^3 (average of listed typical density of 145-155 lb/ft^3). (Listed values from Rinker Materials 1996).

C) Building materials

Cement bought by building material dealers (e.g. Home Depot, Lowes) are sold typically to home owners either in 94-lb bags of Portland cement or in premix concrete mix (including sand and gravel, which the customer will add water to and mix). It is assumed that the raw materials required for this cement (for both patchwork and premix concrete) is similar to 20 MPa ready-mix concrete.

Assume for 'Building materials' (**3.8%** of total cement consumption)

Building materials	**3.8% of total cement consumed**

Table D 10 Raw materials of concrete by type of building material (PCA LCI Portland Concrete 2002)

Raw materials of concrete (kg/m^3 concrete)	**Building materials**
Cement[a]	206
Water	141
Fine aggregate	830
Coarse aggregate	1,100
SCM/fly ash[b]	17
Unit weight	**2,294**

[a] Modified from PCA LCI of Portland Concrete to reflect use of SCMs (in particular fly ash).

[b] Based on 0.0752 kg fly ash/kg cement used in concrete production, as computed in Section 5.2.4

D) Mortar

Masonry cement is dominantly used for making mortar, grout or terrazzo, hence assume for 'Mortar',

Mortar	**4.0% of total cement consumed**

Table D 11 Raw materials of concrete for mortar (ATHENA; Lea 1971)

Raw materials of concrete (kg/m^3 concrete)	**Mortar**
Cement[a]	284
Water	185
Fine aggregate	785
Coarse aggregate	-
SCM/fly ash[b]	23
Unit weight	**1,277**

[a] Modified from PCA LCI of Portland Concrete to reflect use of SCMs (in particular fly ash).

[b] Based on 0.0752 kg fly ash/kg cement used in concrete production, as computed in Section 5.2.4

E) Highways and roads

Road mix	**26.4% of total cement consumed**

Table D 12 Raw materials of concrete for roads (ASHTO, 1974 referenced in Gambatese & Wood, 2002)

Raw materials of concrete (kg/m^3 concrete)	**Roads**
Cement[a]	258
Water	395
Fine aggregate	650
Coarse aggregate	999
SCM/fly ash[b]	21
Unit weight	**2,323**

[a] Modified from PCA LCI of Portland Concrete to reflect use of SCMs (in particular fly ash).

[b] Based on 0.0752 kg fly ash/kg cement used in concrete production, as computed in Section 5.2.4

F) Other infrastructure

It is assumed that all cement used for other infrastructure, which consists of oil and gas well mining, water/waste management (including waste stabilization), mining, utilities, farm construction, other public works and others, is made into 35 MPa concrete (commonly used for most structural applications).

Assume for 'Other infrastructure'

Other infrastructure	**4.8% of total cement consumed**

- Assumed produced on-site.

Table D 13 Raw materials of concrete by type of ready-mixed concrete (PCA LCI Portland Concrete 2002)

Raw materials of concrete (kg/m^3 concrete)	**Other infrastructure**
Cement	335
Water	141
Fine aggregate	710
Coarse aggregate	1,200
Unit weight (kg/m^3)	**2,385**

Section 6.3.2: Allocation of concrete

(ii) Allocation by building type

Table D 14 Historical apparent use of Portland cement by %

	Residential buildings	Public buildings	Industrial and commercial buildings	Farm const-ruction	Streets & highways	Water & Waste Mgmt	Utilities	Others	Total
1998 Apparent Use of Cement Summary	31	8	18	3	26	8	1	5	100
1999 Apparent Use of Cement Summary	31	8	18	3	26	8	1	5	100
2000 Apparent Use of Cement Piechart	22	8	19	4	32	9	1	6	101
2003 Apparent Use of Cement Piechart	31	6	10	5	32	8	1	6	99

[a] Listed as 'Transportation'

[b] Listed as 'Public works'

[c] Listed as 'Miscellaneous uses'

APPENDIX E: 'WASTE MANAGEMENT OF CONCRETE'

E(e) Emissions

Table E 11 Emissions factors for 'Waste management of concrete'

(kg/GJ)	**CO_2**	**SO_2**	**NO_X**	**CH_4**	**CO**	**PM**	**VOC**
Diesel fuel	71.0	0.115	0.656	0.0230	0.649	0.0916	0.115

- Normalized to 1 GJ of energy from PCA LCI of Portland concrete data (estimated based on EPA AP-42 emissions factors).
- Assume 100% diesel.