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The contemporary cement cycle of the United States

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Abstract A country-level stock and flow model for cement, an important construction material, was developed based on a material flow analysis framework. Using this model, the contemporary cement cycle of the United States was constructed by analyzing production, import, and export data for different stages of the cement cycle. The United States currently supplies approximately 80% of its cement consumption through domestic production and the rest is imported. The average annual net addition of in-use new cement stock over the period 2000–2004 was approximately 83 million metric tons and amounts to 2.3 tons per capita of concrete. Nonfuel carbon dioxide emissions (42 million metric tons per year) from the calcination phase of cement manufacture account for 62% of the total 68 million tons per year of cement production residues. The end-of-life cement discards are estimated to be 33 million metric tons per year, of which between 30% and 80% is recycled. A significant portion of the infrastructure in the United States is reaching the end of its useful life and will need to be replaced or rehabilitated; this could require far more cement than might be expected from economic forecasts of demand for cement.

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Introduction

Hydraulic cement is one of the most important construction materials in modern society in terms of both value and volume. Portland cement, the most common type of hydraulic cement, is produced by heating limestone and other raw materials in a rotary kiln to produce an intermediate product called clinker. The clinker is then ground, along with about 5% (by weight) of gypsum, into a fine powder. When combined with water, cement forms a paste that binds sand and gravel (or other coarse aggregates) into a solid compound material known as concrete. Concrete usually contains about 11%–14% by weight of (dry) cement powder. Concrete is the most widely used manufactured material in buildings, bridges, streets, and highways.

Cement production, especially to form clinker, is highly energy intensive; in the United States the average unit energy consumption for cement plants in 2000 was about 5.2 GJ per metric ton of cement.[1] The critical environmental concerns associated with cement production are the large amount of raw materials required to make clinker, and the particulate and gaseous emissions (especially carbon dioxide which is a major greenhouse gas) from the clinker kilns. With respect to carbon dioxide, the cement industry is one of the two largest manufacturing industry sources in the United States, the other being the iron and steel industry.[2]

Concrete use in the United States reflects population growth and urbanization trends. Much of the concrete in use today (within buildings, roads, bridges, and other infrastructure) was installed several decades ago during early phases of growth and urbanization, and there are growing concerns about the condition and performance of this concrete. Various categories of infrastructure in the United States scored an overall grade of D (i.e., poor) in a recent assessment, and it was estimated that necessary replacement, rehabilitation, or both of infrastructure will require an investment of US$1.6 trillion by 2010.[3] This work will increase demand for cement. Apart from the environmental issues related to producing this extra cement, repair, replacement, or both of deteriorated infrastructure also commonly results in societal inconveniences and secondary environmental effects. For example, repair of transportation infrastructure commonly causes delays and detours for vehicular traffic that may lead to greater fuel use and increased vehicular exhaust.

To enhance the performance of concrete infrastructure in the United States and reduce environmental and economic impacts associated with deteriorating infrastructure, efforts are underway to develop advanced composite materials or concretes with greater strength and durability.[4–8] A comparative evaluation of life-cycle costs and environmental management issues for conventional concrete and alternative materials can aid in the selection of the best building materials for repairing or replacing existing infrastructure. Material flow analysis of the cement cycle is a critical component of such a comparative assessment and provides an understanding of resource supply, use, recovery, and recycling at a regional or national scale. Cement is chosen for the direct analysis instead of concrete itself because data on cement production and use are far more abundant and complete than those for concrete.

This article undertakes a preliminary material flow analysis of the contemporary cement cycle of the United States. The objective is to characterize stocks and flows of cement (as a proxy for concrete) over its life cycle and to analyze the underlying environmental and resource use implications. Material flow analysis is based on the universal law of mass conservation and is used to assess the current and future state of material flows and accumulation in the economy and in the environment. Many examples of material flow analysis models can be found in the literature.[9–16]

The present study is a component of the National Science Foundation MUSES Sustainable Concrete Infrastructure Materials and Systems project at the Center for Sustainable Systems, University of Michigan. This study provides an assessment of the flows of cement in the United States over the complete life cycle as characterized by three stages: production, use, and end-of-life disposal (see below for a detailed description of each life cycle stage). The intended purpose of this study to quantify cement flows is to understand the type and amount of raw materials extracted and consumed to produce cement and to estimate how much cement is added as new in-use stock every year, how much is discarded, and how much is disposed of in landfills. Previous material flow studies analyzing cement flows in the United States[1,17] have mainly focused on production-related flows, whereas this study provides a more integrated assessment, emphasizing the material flows for cement at the "end of life" of infrastructure systems.

Overview of the cement cycle

The material life cycle of cement consists of three main stages: production (including raw material extraction and the manufacture of clinker), use (primarily within concrete), and end-of-life disposal (waste management). At each life cycle stage, material can be exchanged among reservoirs (a reservoir is defined as a compartment that contains the resource being studied,[18] including the environment and material imports and exports.

Production of cement

Raw materials for the manufacture of cement are selected to provide the compositional requirements for modern portland cement clinker. Clinker is composed mainly of four oxides: calcium oxide (CaO – about 65% by weight), silica (SiO_2 – about 22%), alumina (Al_2O_3 – about 6%), and iron oxide (Fe_2O_3 – about 3%). Raw materials for cement manufacture are mostly products from the mining industry. The calcium oxide is provided mostly by calcareous rocks such as limestone and marble. The alumina and silica are commonly provided by clay or shale; iron oxide by shale, iron ore, or mill scale; and silica sand is commonly used to remedy any remaining silica shortfalls in the other raw materials. Increasingly, industrial by-products such as ferrous slag and coal combustion fly ash are also being used as raw materials.[1] The contemporary nonfuel raw materials consumption for the manufacture of cement and clinker in the United States is summarized in Table 1. Although Table 1 does not distinguish between raw materials used to make clinker and those used subsequently in the finish mill to make finished cement, overall, about 1.7 metric tons of raw materials are required to produce 1 metric ton of clinker or portland cement. The majority of the apparent loss in mass is due to the emission of carbon dioxide, as will be discussed later. Not shown in Table 1 is the fact that about 0.2 metric tons of (mainly fossil) fuels are consumed per metric ton of clinker manufactured. Overall, cement manufacture also consumes about 100–160 kWh of electricity per metric ton of cement;[1] in the United States, the vast majority of this electricity is purchased from the national grid.

To minimize transportation costs, cement plants are generally located close to their limestone quarries. The limestone is transported from the quarry to the mill of the cement plant, where it is crushed and ground and then proportioned and mixed with various other ground raw materials (as needed) to form the raw mix or feed for the kiln. At the high temperatures reached in the kiln, the raw materials react to produce several cement minerals, chiefly tricalcium silicate and dicalcium silicate (these, when hydrated, provide the cement's binding strength), within a semifused nodular intermediate product called clinker.

From an environmental standpoint, and that of the mass balance, the key reaction in the kiln is the highly energy-intensive calcination (typically at about 750°–1000°C) breakdown of the calcium carbonate ($CaCO_3$) in the limestone to

Table 1. Contemporary nonfuel raw material consumption for the manufacture of cement and clinker in the United States

Material	Consumption[a] (million metric tons per year)
Limestone and similar calcareous rocks	122.3
Clay, shale, others	8.3
Sand and sandstone	3.8
Iron ore, mill scale	1.3
Gypsum and anhydrite	4.9
Slag, fly ash, other ash	4.2
Others	1.2
Raw material equivalent of imported clinker	5.3
Total	**151.4**
Clinker production	81.3
Cement production (portland and masonry)	91.4

Source: van Oss[19]
[a] Averaged over 2000–2004

Table 2. Production of portland cement, masonry cement, and clinker in the United States[a] over the period 2000–2004

Product	2000	2001	2002	2003	2004	2000–2004 average
Portland cement	83 514	84 450	85 283	88 106	92 434	86 757
Masonry cement	4332	4450	4449	4737	5000	4594
Clinker	78 138	78 451	81 517	81 882	86 658	81 329

Data in thousand metric tons
Source: van Oss[19]
[a] Excludes Puerto Rico

form calcium oxide (CaO) plus carbon dioxide (CO_2). The subsequent formation of the actual clinker minerals and the clinker nodules typically requires yet higher temperatures (especially to form tricalcium silicate), but the reactions actually require less thermal energy than does calcination, and there is little further change to the mass balance.

The resulting clinker is interground with gypsum in the finishing mill to produce portland cement; the gypsum is added to control the setting rate of the concrete during cement hydration. More detailed descriptions of cement manufacture are given in the literature.[1,20–22]

In order to improve the performance of concrete and, increasingly, to minimize the environmental impacts of the manufacture of concrete, supplementary cementitious materials (SCM), such as fly ash, ground granulated blast furnace slag, silica fume, and pozzolana (a reactive volcanic ash), may be substituted for some of the portland cement in the finished cement (i.e., to make a blended cement) or in concrete. The extent to which SCM can substitute for portland cement depends mainly on the desired strength, durability, and other properties of the concrete, but substitution rates of 10%–30% or more are common. Apart from potentially improving the quality of the concrete, reducing the portland cement component of the concrete through incorporation of industrial by-products (fly ash and slag) as SCM also reduces the demand for virgin raw materials and the emissions associated with a given volume or mass of concrete. Likewise, the use of industrial by-product SCM in concrete decreases the need for disposal of these by-products, which conserves landfill space.

Use of cement

Production data for portland cement, masonry cement, and clinker for the period 2000–2004 are given in Table 2. Most of the cement produced in the United States is portland cement (approximately 87 million metric tons per year). Portland cement is primarily utilized to make concrete, which has a wide spectrum of uses, including construction of roads, buildings, bridges, pavements, foundations, and storage tanks. Compared to that of portland cement, the amount of masonry cement produced is very small; masonry cement is primarily used in the construction of buildings. Detailed cement usage data are available only from the United States Geological Survey (USGS) and from the Portland Cement Association (PCA); the former provides data on the distribution of portland cement shipments to different customer types, and the latter provides data on the end uses of cement. During the period 2000–2004, approximately 90% of portland cement shipments were made to ready-mixed concrete and concrete product producers,[19] as shown in Fig. 1. The data from the PCA averaged over the period 2000–2004 show that the cement end-use market was dominated by buildings (residential – 33%, commercial – 7%, public – 8%, and industrial – 4%) and streets and highways (29%), followed by water and waste management (6%) and other miscellaneous uses (12%).[23]

End-of-life management of cement

Concrete in each of its uses has a certain useful lifespan. For example, streets and highways in the United States are expected to last 45 years, whereas residential buildings have an average lifetime of 80 years.[24] The difference reflects the fact that streets and highways deteriorate more rapidly owing to their high degree of environmental exposure (to moisture, freezing and thawing, and chemicals such salt and sulfate) and the exposure to vehicular traffic. During the lifespan of each concrete structure, there are typically several cycles of repair and renovation. At their end of life, concrete structures are usually demolished. The further reuse of concrete construction and demolition (C&D) debris depends on a number of factors such as its physical characteristics (porosity, density), the economic viability, and construction and material standards.[25] The average material composition of construction and demolition debris associated with buildings is given in Table 3. The concrete fraction is higher in nonresidential buildings because the wall material in many of the residential buildings in the United States is not concrete. The amount of concrete debris from construction of new buildings is low because the amount of concrete to be poured is usually closely estimated using standard mix designs, and the amount of losses onsite are relatively small.[26]

In terms of reuse, it is more difficult to recover and recycle individual C&D materials from the demolition of buildings than from streets and highways because the debris from buildings is more heterogeneous.[29] There are a number of advantages of in-place recycling of crushed concrete aggregate at highway sites, and a number of States in the United States are promoting such recycling.[30] The reuse of crushed concrete aggregate from the existing pavement simplifies construction of new pavement at existing grade on highways.[31] However, the specifications for construction materials do not promote reuse of materials already in use in the infrastructure.[32]

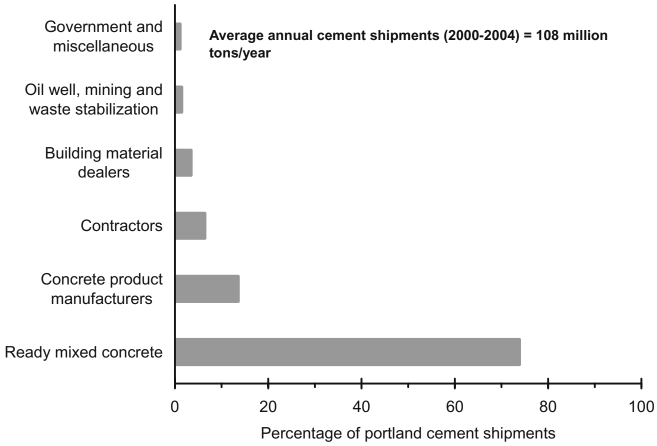

Fig. 1. Distribution of portland cement shipments by type of customer in the United States over the period 2000–2004 (van Oss[19]). Concrete product manufacturers include those of concrete bricks and blocks, precast and prestressed concrete, concrete pipes, and others. Contractors include those involved with airports, road paving, soil cement, and others

Methodology

The concepts of material flow analysis were used to construct the contemporary cement cycle. The spatial boundary chosen for this study was the United States excluding Puerto Rico (so as to maintain data consistency as per USGS data). For the cement cycle, annual flow magnitudes for the production reservoir were averaged for the period 2000–2004 (data for use and end-of-life reservoirs are for 2002). The mass balance estimates for the production reservoir were determined as follows:

$$\text{Net cement flow} = \sum \text{Production} + \sum \text{Import} - \sum \text{Export} + \text{Change in Stocks} \quad (1)$$

The net cement flow can also be called the apparent consumption of cement. The flows to and from the production reservoir were broken down to three subreservoirs (mine–mill complex, kiln, and finishing mill) to characterize the production and net trade (= import–export) flows of raw materials, clinker, and cement. Within the production reservoir, there could be net depletion or addition of material to clinker and cement stockpiles, depending on changes in inventory over the calendar year.

Table 3. Average material composition of construction and demolition debris associated with buildings

Building type	Total waste generation (million metric tons)[a]	Wood (%)[b,c]	Drywall (%)[b,c]	Metals (%)[b,c]	Concrete (%)[a,b,c]	Plastics (%)[b,c]	Other materials (%)[b,c]
Residential							
New construction	7	53	19	2	5–9	2	15
Renovation	13	37	31	3	5	<1	<24
Demolition	20	33	10	4	27–33	1	25
Nonresidential[d]							
New construction	4	31	23	10	5–33	3	–
Renovation	28	28	22	19	22–35	3	6
Demolition	45	21	10	7	53–66	3	6

[a] Sandler[26]
[b] HQ AFCEE[27]
[c] USEPA[28]
[d] Does not include roads, highways, and bridges

Production residues consist of mine overburden (generally minor); crushed limestone screenings (also known as stone dust or fines and are commonly used as a raw material for clinker production); cement kiln dust (CKD); carbon dioxide emissions from the calcination phase of the clinker production process; and other, volumetrically lesser, amounts of gaseous emissions from the kiln such as nitrogen oxides, sulfur oxides, and water vapor. In addition, there are carbon dioxide emissions from fuel combustion during clinker production. Mine overburden is the material moved during the extraction of the cement raw materials that is not used either for cement manufacture or for other purposes (e.g., sold as aggregates). Rock fines are material that passes through the smallest screen used in the raw materials processing circuits; of issue here are any fines not used as a raw material. CKD comprises fine particulate matter or dust that is generated in the kiln line; the material is essentially captured, but it may or may not be recycled to the kiln. If CKD is not recycled, it is generally landfilled, although it can be used as a soil liming agent or as a fill material.

This material flow analysis accounts for the flows and transformation of only the nonfuel materials used to make clinker and cement; the flows of energy resources and emissions related to fuel combustion are not evaluated in this study. Fuel tonnages and carbon dioxide emissions related to fuel combustion are discussed by van Oss and Padovani.[2] Integrated assessment of energy and material flows are more data intensive and methodologically challenging and therefore the scope of this study is limited to material flows only.

Estimates for cement cycle flow parameters

For this study, mine overburden and (unused) stone fines were estimated as 6% and 1%, respectively, of crushed rock production from limestone quarries, following the findings of Matthews et al.[33] Output of CKD was estimated at 0.2 metric ton per metric ton of clinker, based on the discussion by van Oss and Padovani;[2] as noted by these authors, CKD data are subject to high uncertainties. Carbon dioxide emissions from calcination were estimated to be 0.51 metric ton of carbon dioxide per metric ton of clinker[2] and are based on straightforward stoichiometric considerations. The data on production, imports, exports, and changes in stockpiles of clinker and cement are from USGS assessment of the cement industry and official trade data;[19] the data sources are summarized in Table 4.

The cement produced in the United States, as well as the net imports of cement, enter the use reservoir, and the cement flow within the use reservoir is divided into subflows: additions to stock (i.e., new construction); repair/renovation; and retirement. Direct data on the breakout of cement sales (consumption) into new construction and repair/renovation are not available from USGS data on cement consumption; however, the PCA has developed indices that relate the tonnage of cement to the dollars spent, but mostly in terms of types of construction, as shown in Table 5. The PCA's tonnage ratio for new versus renovation residential construction (for the 5-year average of the period 2000–2004) is 75%–25%. Alternatively, this breakout between new and renovation construction can also be estimated by using the real dollar value of construction data and estimates of the cement intensity (tons per million dollars of spending) of different types of construction (Sullivan 2006, personal communication). The Construction Expenditures Branch of the U.S. Census Bureau (USCB) reports the annual total value of construction. However, only the data for private residential construction (current US$2200 billion total over the period 2000–2004[34]) has any breakout for repair or renovation, i.e., new housing units (new single family – current US$1400 billion; new multi-

Table 4. Production flows for cement

Process	Flow name	Flow characterization	Data sources
Mine	Crushed rock	Raw material inputs to mine obtained from literature	van Oss[19]
	Mine overburden	Estimated as 6% of crushed rock production. Assumed to be landfilled	Matthews et al.[33]
	Stone fines	Estimated as 1% of crushed rock production: assumed 100% is recycled	Matthews et al.[33]
Kiln	Clinker	Production data from literature. Assumed uniform composition of production and imports	van Oss[19]
	Clinker stockpile	Year-end clinker stock data from literature	van Oss[19]
	Cement kiln dust (CKD)	Generation estimated as 20% of clinker production. Assumed 67% of total CKD is recycled in the kiln and the remainder is landfilled	van Oss and Padovani[2]
	CO_2 emissions	Estimated based on the literature	van Oss and Padovani[2]
Finishing mill	Gypsum	Data from literature	van Oss[19]
	Cement	Data from literature	van Oss[19]
	Cement stockpile	Year-end cement stockpile data from literature	van Oss[19]

Table 5. Value of construction put in place and cement consumption by type of construction in the United States over the period 2000–2004

	Constant 1996$ billion	% of $	Million metric tons	% of tonnage	Metric tons/$million
Residential	$1740.2	100	180.043	100	103.4
New	$1244.1	71	135.752	75	109.1
Repair/renovation	$490.1	29	44.292	25	90.4
Highways	$221.1		158.353		716.2

Source: Portland Cement Association[23]

family – current US$200 billion) and improvements (current US$600 billion). As part of its annual highway finance statistics, the Federal Highway Administration (FHWA) reported Federal and State funding for highways and bridges as totaling current US$279 billion for the period 2000–2004, split out as about 60% for new construction (current US$162 billion over 2000–2004) and about 40% for repair and rehabilitation (current US$117 billion over 2000–2004).[35] Based on the weighted average of the USCB and FHWA data over the period 2000–2004, 70% of the total consumption tonnage of cement in the United States is estimated to have been used for new construction and the remaining 30% for repair and renovation activities. Although adoption of PCA or USCB/FHWA breakout ratios of cement consumption for new and renovation construction are significantly different, the likely error in using any one of the approximations would be in the range 5%–10%. Therefore, for this study, we assume that the breakout ratio between new and renovation construction is 65 : 35. It also can be anticipated that repair and rehabilitation of deteriorating highways currently in use would push the renovation component of cement consumption to a higher value. It is important to note that new construction projects are expected to consume more concrete overall than repair and renovation work, and that unit prices for concrete will generally be lower for large projects than for small projects.

New construction, repair/renovation activities, and demolition of old infrastructure all generate C&D debris. Estimates of C&D debris from residential and nonresidential buildings were derived from a U.S. Environmental Protection Agency (USEPA) report[28] and modeling by Kapur et al.;[36] the latter study also models roads, bridges, highways, and other civil infrastructure. The in-use cement stock was estimated as the difference between cement entering the use reservoir and cement discards in the form of C&D debris exiting the use reservoir. The net trade flows of cement within finished products (e.g., concrete tiles) were excluded owing to the lack of data on the cement content of these products.

In the end-of-life reservoir, concrete can be either recycled to the use reservoir or disposed of to the environment (landfills). There also could be net import–export flows (likely minor) of C&D debris containing cement discards. Data on recycling of C&D debris are limited. The USGS reports that 9.5 million metric tons of concrete were recycled in the United States in 2000,[37,38] but these data are likely to be incomplete. For onsite C&D debris, the Associated General Contractors of America (AGC) conducted in 2004 a survey on the recycling practices of about 300 contractors. This survey showed that, depending on the type of the project (building, highway, utility, or demolition), the recycling rate for the concrete fraction of the C&D debris generated varied from 33% to 100% (Table 6).

Similar surveys have also been carried out by the Construction Materials Recycling Association (CMRA) and the National Demolition Association (NDA) (Taylor 2006, personal communication; Turley 2006, personal communication).[39] The CMRA survey estimated that overall in the United States, generation of C&D wastes from buildings

Table 6. Concrete recycling rates of construction and demolition projects in the United States

Type of project	Recycling rate (%)
Building construction	67–100
Highway construction	33–100
Utility construction	50–100
Demolition work	57–100

Data provided by Melinda Tomaino Flores, Associated General Contractors of America

(i.e., not including highways and bridges), consisting mainly of concrete, metals, wood, and asphalt shingles, is approximately 325 million metric tons per year.[40] Further, although no breakout between generation and recycling rates are provided for the different types of C&D debris, the CMRA survey shows that, overall, about 130–140 million metric tons of concrete (again, excluding debris from highway, road, and bridge construction and demolition debris) are recycled every year. The cement content of that concrete would be in the order of 16–17 million metric tons.

Kapur et al.[36] used a dynamic substance flow model based on a range of different lifetime distribution values for each cement end-use infrastructure application and estimated contemporary cement debris generation from all end-use sectors in the United States to be in the range of 24–35 million metric tons per year (ca. 2002). This suggests that cement debris from bridges, highways, and roads, for which direct data are lacking, is in the range 8–18 million metric tons per year.

Although restricted to demolition debris, the NDA survey estimated that, of about 115 million metric tons of concrete debris generated annually in the United States, 73% is currently recycled or reused.[39] USEPA in its 1996 study estimated that recovery of total C&D debris in the United States was in the range 20%–30%,[28] and that estimate seems not to have changed in the past few years.[41,42] Sandler[26] estimated the concrete recycling rate to be in the range 50%–57%. In an ongoing effort to update its estimates on C&D debris generation, composition, recovery, and recycling, USEPA estimated that 80% of recovered concrete in C&D debris is recycled and reused as fill or aggregate (Dunn 2006, personal communication).

In an attempt to reflect the wide range and high uncertainty of these estimates, we have used the range 30%–80% for the recycling rate for concrete; the remaining 20%–70% of the concrete debris was assumed to be landfilled.

Results and discussion

The contemporary cement cycle of the United States for the period 2000–2004 is shown in Fig. 2. For this period, an average of approximately 140 million metric tons per year of raw materials in the form of crushed rock, slag, and ash were consumed to produce an average of 81 million metric tons per year of clinker. The largest component of the raw materials consumed to make clinker (typically about 85%–90% of the total weight of nonfuel raw materials) is lime-

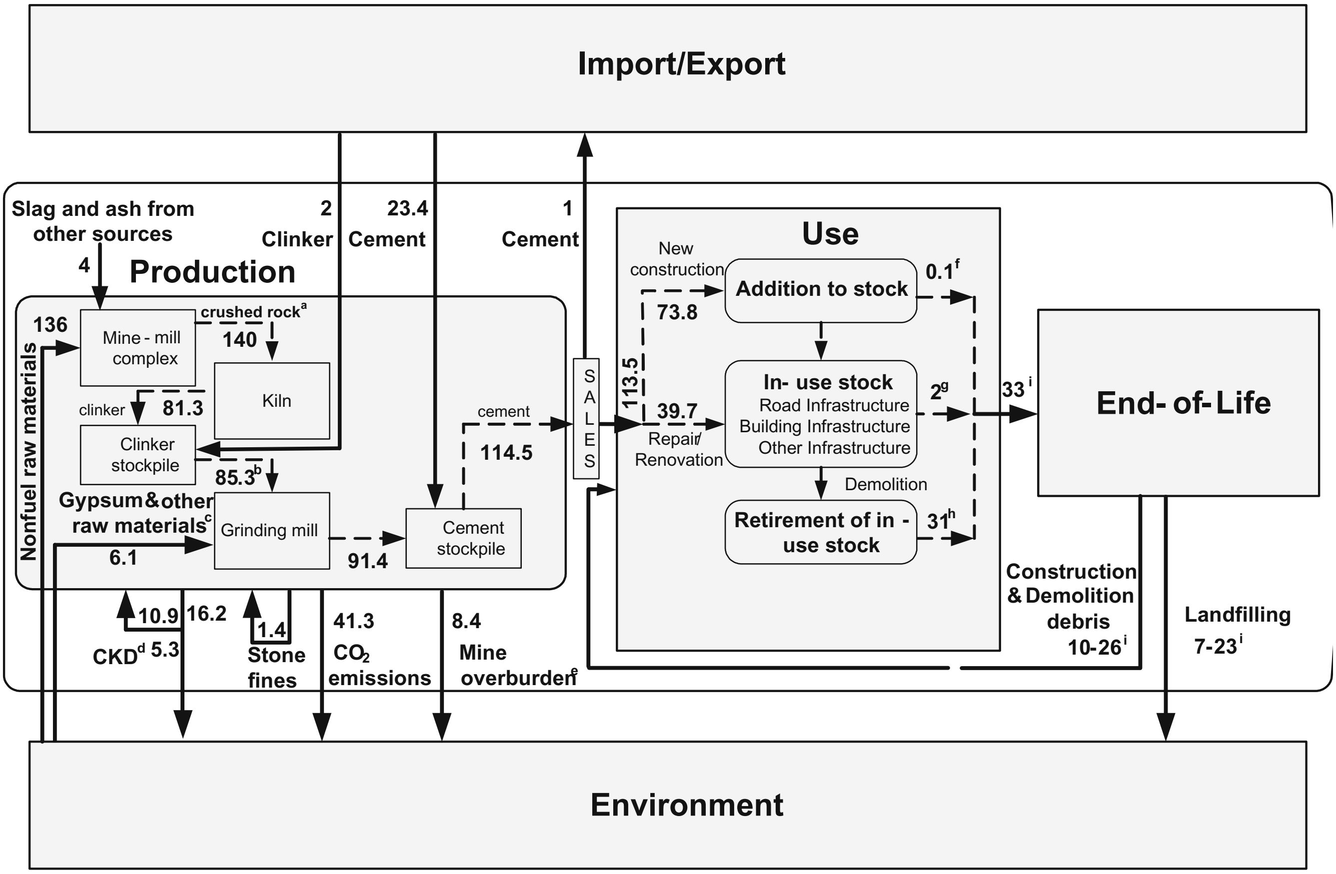

Fig. 2. Contemporary cement cycle of the United States (production data are averaged over the 2000–2004 period). For use and end-of-life reservoirs, the data are representative of 2002. All units are in million metric tons per year. *a*, Includes industrial by-products (e.g., ash and slag). Some additional raw material components are partly contributed by fuels (e.g., ash from coal), not shown. *b*, Includes net depletion of 1.6 million metric tons of clinker from the stockpile, this represents the inventory change over the 2000–2004 period. *c*, Excludes raw material equivalent of imported clinker. *d*, Cement kiln dust (*CKD*). *e*, The mine overburden is usually utilized to backfill the quarry. *f*, Discards from new construction activities as per USEPA.[28] New construction activities include only residential and nonresidential sectors (including public and commercial buildings, but excluding highways, bridges, and roads). *g*, Discards from repair and renovation activities as per USEPA.[28] Repair and renovation activities include only residential and nonresidential sectors (including public and commercial buildings, but excluding highways, bridges, and roads, which are included with the discards from demolition). *h*, Discards from demolition activities from residential and nonresidential sectors (including public and commercial buildings) and from highways, roads, and bridges as per Kapur et al.[36] *i*, Cement content of concrete discards. Note that CO_2 emissions are for calcination only; emissions from fuel combustion are not included, but are slightly lower than this figure

stone and other materials containing calcium carbonate. Data are lacking on the actual generation of mine overburden and (unused) stone fines in the quarrying of cement raw materials, but based on Matthews et al.,[33] the fact that stone fines (if chemically suitable) can readily be utilized as raw materials, and the fact that overburden material can ultimately be "used" to backfill the quarry, an upper limit on these production residues may be estimated at about 9.8 million metric tons, of which 1.4 million metric tons is assumed to be recycled.

In addition to the clinker, about 6 million metric tons of gypsum and other raw materials were added in the finish mill to produce cement. For the study period, clinker production capacity in the United States was inadequate to meet cement demand; accordingly, additional cement was imported and cement was also made from imported clinker. Officially reported imports of clinker for consumption were approximately 2 million metric tons per year. However, the imports were probably higher than this because individual shipments into the United States below a value of US$2000 (common for imports by truck) are not included in official import statistics.[19]

To simplify the characterization of the flows, it is assumed that 100% of clinker output and imports initially go into a collective stockpile before feeding the finish mill. Similarly, 100% of cement production and imports go into a cement stockpile before entering the sales reservoir. During the period 2000–2004, there was net depletion of year-end clinker stockpiles by 2.0 million metric tons and net addition of cement stockpiles by 0.3 million metric tons. However, regarding cement and clinker stockpiles, the cement industry reports data only for the beginning and end of each calendar year (and only the year-end stockpile data are published), and these inventory dates are a matter of convenience. In fact, stockpiles of cement and clinker fluctuate throughout the year depending on the state of the economy, weather (affects construction demand for cement), and maintenance and shutdown schedules of kilns and grinding circuits at cement plants. Therefore, changes in year-end stockpiles have little quantitative significance and, in any case, are small relative to the overall production and sales flows.

Annual consumption of cement, defined as sales to final end-use customers, in the United States averaged about 114 million metric tons per year over the period 2000–2004. As with clinker production, cement production capacity in the United States was inadequate to meet demand during this period, and imported cement and clinker accounted for an average of 20% of cement consumption, or 25 million metric tons per year.[19] The United States exported an average of only about 1 million metric tons of cement per year over this period.

Average annual carbon dioxide emissions owing to calcination were approximately 41 million metric tons per year over the 2000–2004 period. Carbon dioxide emissions from fuel combustion, which are slightly lower than those from calcination (based on data for 2000 in van Oss and Padovani[2]), are not included in this analysis.

The amount of CKD generated over the 2000–2004 period was estimated to average about 16 million metric tons per year. Approximately two-thirds of the CKD generated was captured and returned to the kiln and the remaining CKD was either disposed of in landfills, sold as a soil conditioner, or used for backfilling.[2]

A mass balance closure check was performed on the production reservoir, and the inflows exceeded the outflows by 0.3 million metric tons. This unaccounted-for flow represents just 0.2% of the inflows, indicating the consistent and high quality of cement and clinker production data compared with material flow analysis studies for other commodities (e.g., Graedel et al.,[12,13]). Apart from issues concerning the applicability of year-end stockpile data, part of the discrepancy may be because raw material flows do not include nonfuel components of fuels (e.g., ash in coal, steel in used tires) that contribute to the oxide requirements for clinker production. Also, the reported weight of raw materials includes a variable amount of moisture (reporting is not necessarily on a dry basis). The production and related data do contain potential component errors – even "reported" production data are accurate to only about 1% or so.

The average amount of cement entering the use reservoir from the sales reservoir over the 2000–2004 period was 114 million metric tons per year. As assumed above, approximately 65% of cement consumed was for construction of new structures and the remainder was consumed for repair and renovation activities. After subtracting the flow to the end-of-life reservoir, the average annual net addition of new cement stock to the use reservoir is seen to be approximately 80 million metric tons per year.

In a 1996 study, USEPA estimated that the amount of cement in concrete discards in C&D debris generated from the residential and nonresidential sectors (i.e., excluding highways, roads, and bridges) was approximately 6 million metric tons.[28] For the current study, the EPA's 6 millions metric tons of discards was extrapolated to 7 million metric tons for 2002 (the midpoint for the period 2000–2004) on the assumption that the rate of increase of discards was proportional to the increase in gross domestic product. This flow of 7 million metric tons per year is a component of the 33 million metric tons per year flow from the use reservoir to the end-of-life reservoir. The 7 million metric tons per year can be broken down into debris from new construction activities (shown in Fig. 2 as the approximately 0.1-million-metric-ton flow exiting the addition-to-stock subreservoir), debris from repair and renovation work projects (shown as the 2-million-metric-ton flow exiting the in-use stock subreservoir), and 5 million metric tons of demolition debris (included in the 31-million-metric-ton flow exiting the retirement subreservoir). This 31 million metric tons per year of cement debris exiting the retirement subreservoir represents the median quantity for total retirement discards for 2002 from Kapur et al.,[36] rather than the USEPA estimate for demolition discards (which does not include highways and bridges). This amount of 31 million metric tons per year is the dominant component of the total flow to the end-of-life reservoir (Fig. 2). Approximately 26 million metric tons per year of this flow represents C&D debris from roads and bridges.

Based on the recycling rate of 30%–80%, the amount of cement in C&D debris recycled from the end-of-life reservoir to the use reservoir is 10–26 million metric tons per year within a much larger tonnage of recycled concrete. The remaining discards (7–23 million metric tons per year) are assumed to be landfilled.

A number of factors account for the large variation in the estimate of concrete recycling rates, including variation in the degree of recycling across different States or regions in the country. Crushed concrete discards are used mostly for low-grade applications such as road base or the filling of low-lying areas,[25] but are rarely used for new concrete applications. There is a high degree of variability in the management, disposal, and transportation costs of C&D debris and the availability of competing virgin aggregate. Each of the States' Departments of Transportation have different polices and practices regarding the use of C&D debris.[31]

No foreign imports of C&D debris are shown in Fig. 2, although they are known to have taken place in very small amounts [e.g., in 2002, Canada exported approximately 16 000 metric tons of C&D debris to the United States (assuming the density of C&D debris[43] to be 0.28 Mg/m^3)].[44,45]

Assuming the cement component of concrete to be 12.5% by weight, the average annual net addition of 81 million metric tons per year of new cement to in-use concrete stock in the infrastructure of the United States over the 2000–2004 period corresponds to a net addition of concrete of about 650 million metric tons per year. On a per capita basis, the amount of concrete consumed yearly over that period in the United States was about 2.3 metric tons.

Significance and implications of the study

The civil infrastructure stock in the United States is rapidly deteriorating. As more and more stock reaches its end of life, the amount of cement debris is expected to increase significantly over the next few decades. General economic indicators predict a trend of slight to moderate growth in the consumption of cement in the United States over the next decade.[50] However, when the surge in the replacement of infrastructure begins, this approach may underestimate the demand for cement. This study estimated that the average rate of use of cement in the United States over the period 2000–2004 was approximately 114 million metric tons per year, of which 65% was utilized for new construction stock and the remaining 35% was utilized for repair and renovation of existing stock and to replace old retiring stock.

As more and more infrastructure reaches its end of life, the contemporary waste generation of approximately 33 million metric tons per year will increase and, as a result, this will create demand for new cement which will be required for replacement of some of the retired infrastructure systems. This requirement for replacement will be in addition to the demand of cement for new construction to meet the needs of population and economic growth and urbanization. This additional demand for cement (and for other raw material used in concrete) has implications for balancing production additions (in terms of tonnage and location of new plant, which are determined by economics of resource availability, regional supply and demand, and transportation to end users) and reliance on imports (the gap between domestic production and consumption of cement has been widening over the past few decades, as shown in Fig. 3).

The retirement of old cement stock has significant environmental and resource management implications. As stated above, it will provide impetus to the growing demand for cement. Cement production has a relatively large environmental footprint (e.g., the mining of raw materials, use of fuels, and carbon dioxide emissions). To reduce its footprint, the cement industry would need to continuously improve its energy efficiency and adopt cleaner production practices. Likewise, the disposal of C&D debris has an environmental footprint (landfilling): only part of the C&D debris is currently being recycled, and an increasing volume of C&D disposal to landfills will be a growing problem unless the reuse of this material is increased. However, it should be noted that this material does not replace new cement. End-of-life concrete discards are usually crushed and used as road base or fill material. This type of recycling of materials where it is recycled into a material of inferior quality is known as down cycling. The build up of recycled concrete in the technosphere as a result of down cycling has not been considered as addition of secondary cement stock in the cement cycle presented in this study. This is because recycled concrete cannot be considered to be equivalent to concrete produced from fresh cement, as its physical characteristics and applications are not the same as cement,

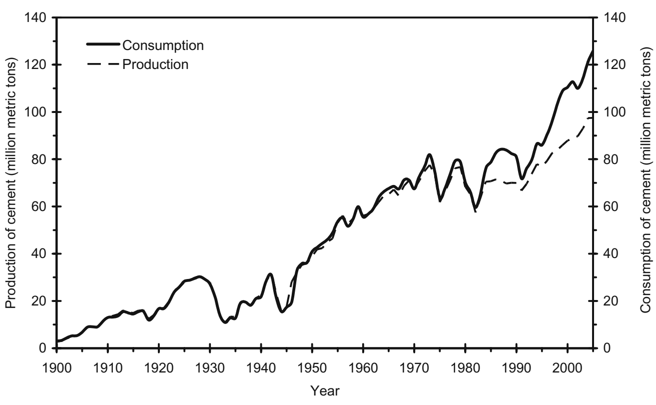

Fig. 3. Production and consumption of cement in the United States from 1900–2005 (van Oss and Kelly[47])

The use of alternative raw materials in clinker production and the use of supplementary cementitious materials as partial substitutes for portland cement in concrete can decrease, on a unit basis, the virgin raw material flows and the emissions associated with portland cement production. Simultaneously, building contractors and structural engineers would need to develop innovative construction methods that can reduce wastage of cement during construction and lower the cement intensity of infrastructure systems.

The construction and demolition industry will have new business opportunities as the generation of concrete discards increases. The concrete fraction of the C&D waste stream is estimated to have been growing at a rate of 4% per year over the past decade (Kapur et al.[37]). The amount of municipal solid waste (MSW) generated in the United States grew at a rate 5% per year over the period 1994–2004.[52] The growth of the C&D waste stream would exacerbate the challenges faced by Federal and State agencies to site new landfills for disposal of MSW. In addition, given the lack of data on generation, recovery, and reuse of C&D debris, it will require concerted efforts by all stakeholders – regulatory agencies, departments of transportation, and the C&D industry – to minimize the amount of C&D debris disposed of in landfills.

The durability of infrastructure is the key parameter that influences the sustainability of the cement cycle. From a sustainability perspective, the service life of infrastructure reflects its durability. A durable infrastructure will last longer and require fewer inputs for repair and maintenance and result in reduced emissions of carbon dioxide (approximately 1 metric ton of carbon dioxide per metric ton of portland cement) because there will be less demand for cement. Analyzing stocks and flows of the cement cycle over a longer time scale can help us to understand the following important aspects with regard to durability and sustainability: (a) The amount of raw materials mobilized to produce cement, (b) the amount of production residues generated during cement production, (c) the proportion of cement use for the replacement of old stock and the addition of new stock, (d) and the amount of time cement remains in use until it is discarded at end of life. If we can improve the strength of cement and the durability of concrete, perhaps we can also reduce the amount of cement/concrete needed for a given type of concrete structure. In addition, efforts are being made to develop more durable concrete such as engineered cementitious composites.

Consumption of cement and other construction materials is expected to grow in the long term owing to increased demand for housing and the expansion, renovation, and reconstruction of infrastructure. A comprehensive assessment of flows and stocks of construction materials will help key stakeholders to improve the life-cycle management of infrastructure systems in the United States. The flows of construction materials form a significant proportion of total nonfuel and nonfood raw material flows entering the United States' economy and, therefore, represent an opportunity to contribute toward achieving the goal of sustainable development.

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