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# Life Cycle Inventory of Portland Cement Manufacture

by Medgar L. Marceau, Michael A. Nisbet, and Martha G. VanGeem

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# KEYWORDS

Cement, energy, emission, life cycle inventory

# ABSTRACT

This report is an update of *Life Cycle Inventory of Portland Cement Manufacture* published in 2002. The purpose of this update is to incorporate the most recent energy use data from the Portland Cement Association's annual *U.S. and Canadian Labor-Energy Input Survey*. The results of the latest *U.S. Environmental R&D Project Questionnaire* also are included. This is a significant update because it includes high quality data on water usage, fuel and raw material consumption, and transportation modes and distances.

The life cycle inventory (LCI) was conducted according to the guidelines proposed by the International Organization for Standardization in ISO 14040, *Environmental Management - Life Cycle Assessment - Principles and Framework* and ISO 14041, *Environmental Management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis*.

The goal is to present the most accurate data on the inputs and emissions related to manufacturing portland cement. The LCI of portland cement is the basis of the LCI of concrete, concrete products, and concrete structures. These LCIs are used in turn to conduct life cycle *assessments* of concrete structures and other structures containing concrete.

The scope is defined by the functional unit of portland cement and the system boundary. The function unit is a unit mass of portland cement manufactured in the United States from domestically produced clinker. The system boundary includes: quarry operations, raw meal preparation, pyroprocessing, finish grinding, and all the transportation associated with these activities.

The LCI data and results are presented for each of the four cement plant processes (wet, long dry, dry with preheater, and dry with preheater and precalciner) and for the U.S.-production weighted average.

The primary difference among the four cement plant processes is energy consumption. The wet process, which feeds raw material to the kiln as a slurry, averages 6.4 GJ/metric ton (5.5 MBtu/ton) of cement compared to dry process with preheater and precalciner which averages 4.2 GJ/metric ton (3.6 MBtu/ton) of cement. The weighted average for all four processes is 4.8 GJ/metric ton (4.1 MBtu/ton) of cement. This represents a 10% decrease from the 2002 report. The pyroprocess step uses 88% of the total fuel and 91% of the total energy. Finish grinding accounts for approximately 50% of the electricity consumption.

Emissions can vary considerably from plant to plant and according to cement plant processes. Carbon dioxide ($CO_2$) emissions are primarily from the calcination of limestone and combustion of fuel in the kiln. Average $CO_2$ emissions from calcination are 553 kg/metric ton (1,110 lb/ton) or 60% of total $CO_2$ emissions. Average $CO_2$ emissions from fuel combustion are 365 kg/metric ton (729 lb/ton) or 39% of total $CO_2$ emissions. The $CO_2$ emissions from fuel combustion are greatest in the wet process and least in precalciner process, reflecting relative plant efficiencies.

# REFERENCE

Marceau, Medgar L.; Nisbet, Michael A., and VanGeem, Martha G., *Life Cycle Inventory of Portland Cement Manufacture*, SN2095b, Portland Cement Association, Skokie, Illinois, USA, 2006, 69 pages.

Revised April 2010: Tables 21a, 21b, 24a, and 24b were corrected for HCl, dioxin and furan values.

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# DEFINITIONS

**Ancillary material.** Material that is used by the system producing the product but is not used directly in product formation; for example, refractory brick in cement kilns.

**Data quality.** Quantitative and qualitative aspects of data and the methods by which they are measured or calculated, collected, and integrated into a life cycle model. The proposed use of the model establishes the quality standards.

**Environmental impact.** Consequences for human health, for the well-being of flora and fauna, or for the future availability of natural resources.

**Functional unit.** Measure of the performance of the functional output of the product or services system; for example, in the cement LCI the functional unit is one unit mass of cement.

**Impact assessment.** Understanding and evaluating the magnitude and significance of environmental impacts.

**Life cycle inventory analysis.** Quantification of the inputs and outputs—materials, energy, and emissions—from a given product or service throughout its life cycle.

**Life cycle.** Consecutive and inter-linked stages of a product or service from the extraction of natural resources to final disposal.

**Life cycle assessment.** A systematic method for compiling and examining the inputs and outputs of a life cycle inventory and the environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle.

**Sensitivity analysis.** Systematic procedure for estimating the effects of data uncertainties on the outcome of an LCA model.

**System boundary.** Interface between the product or service system being studied and its environment or other systems. The system boundary defines the segment of the production process being studied.

**Upstream profile.** The resources consumed and emissions from extracting, processing, and transporting a material or energy source entering the system; for example, the inputs and emissions incurred in delivering a unit mass of coal to a cement plant.

# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| **AP-42** | U.S. Environmental Protection Agency Compilation of Air Pollution Emission Factors |
| **$CH_4$** | Methane |
| **CKD** | Cement kiln dust |
| **CO** | Carbon monoxide |
| **$CO_2$** | Carbon dioxide |
| **HCl** | Hydrogen chloride |
| **Hg** | Mercury |
| **kWh** | Kilowatt-hour |
| **GJ** | Gigajoule ($1\times10^9$ Joules) |
| **LCA** | Life cycle assessment |
| **LCI** | Life cycle inventory |
| **MBtu** | Million British thermal units ($1\times10^6$ Btu) |
| **$NO_x$** | Nitrogen oxides |
| **PM** | Total filterable airborne particulate matter |
| **PM-10** | Particulate matter with a median mass aerodynamic diameter less than or equal to 10 micrometers |
| **PM-5** | Particulate matter with a median mass aerodynamic diameter less than or equal to 5 micrometers |
| **SI** | International System of Units |
| **$SO_2$** | Sulfur dioxide |
| **VKT** | Vehicle kilometer traveled |
| **VMT** | Vehicle miles traveled |
| **VOC** | Volatile organic compounds (does not include methane in this report) |

# Life Cycle Inventory of Portland Cement Manufacture

by Medgar L. Marceau, Michael A. Nisbet, and Martha G. VanGeem*

## INTRODUCTION

This report is an update of *Life Cycle Inventory of Portland Cement Manufacture* (Nisbet, Marceau, and VanGeem 2002). The purpose of this update is to incorporate the most recent energy use data from the Portland Cement Association's annual *U.S. and Canadian Labor-Energy Input Survey*. The results of the latest *U.S. Environmental R&D Project Questionnaire* are also included. This is a significant update because it includes high quality data on water usage, fuel and raw material consumption, and transportation modes and distances.

A life cycle inventory (LCI) is a compilation of the energy and material inputs and the emissions to air, land, and water associated with the manufacture of a product, operation of a process, or provision of a service. An LCI is the first step of a life cycle assessment. During the assessment phase, the social, economic, and environmental aspects are evaluated. The results can be used to choose among competing alternatives the one that has the most favorable attributes. Life cycle assessments of concrete and concrete structures previously have been completed (Nisbet and others 2002; and Marceau and others 2002a, 2002b, and 2002c). These reports will be revised eventually with the results of this update.

This LCI follows the guidelines proposed by the International Organization for Standardization in ISO 14040, *Environmental Management - Life Cycle Assessment - Principles and Framework* (ISO 1997) and ISO 14041, *Environmental Management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis* (ISO 1998).

## DEFINITION OF GOAL AND SCOPE

### Goal

The goal of this LCI is to present the most accurate data on the inputs and emissions related to manufacturing portland cement. The LCI of portland cement is the basis of the LCI of concrete, concrete products, and concrete structures. These LCIs are used in turn to conduct life cycle *assessments* of concrete structures and other structures containing concrete.

### Scope

The scope of the LCI is defined by the function of portland cement, the functional unit, and the system boundary.

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**Product function.** Portland cement is a hydraulic cement composed primarily of hydraulic calcium silicates. Hydraulic cements harden by reacting chemically with water. During this reaction, cement combines with water to form a stonelike mass, called paste. When the paste (cement and water) is added to aggregates (sand and gravel, crushed stone, or other granular materials) it binds the aggregates together to form concrete, the most widely used construction material. Although the words "cement" and "concrete" are used interchangeably in everyday usage, cement is one of the constituents of concrete. Cement is a very fine powder and concrete is a stonelike material. Cement constitutes 7% to 15% of concrete's total mass by weight. Using cement LCI data incorrectly as concrete LCI data is a serious error.

**Cement manufacturing process.** The cement manufacturing process is described below and in more detail in the Appendix. This description is taken from the section on portland cement in the Air Pollution Engineering Manual (Greer, Dougherty, and Sweeney 2000). A diagram of the process is shown in Figure 1.

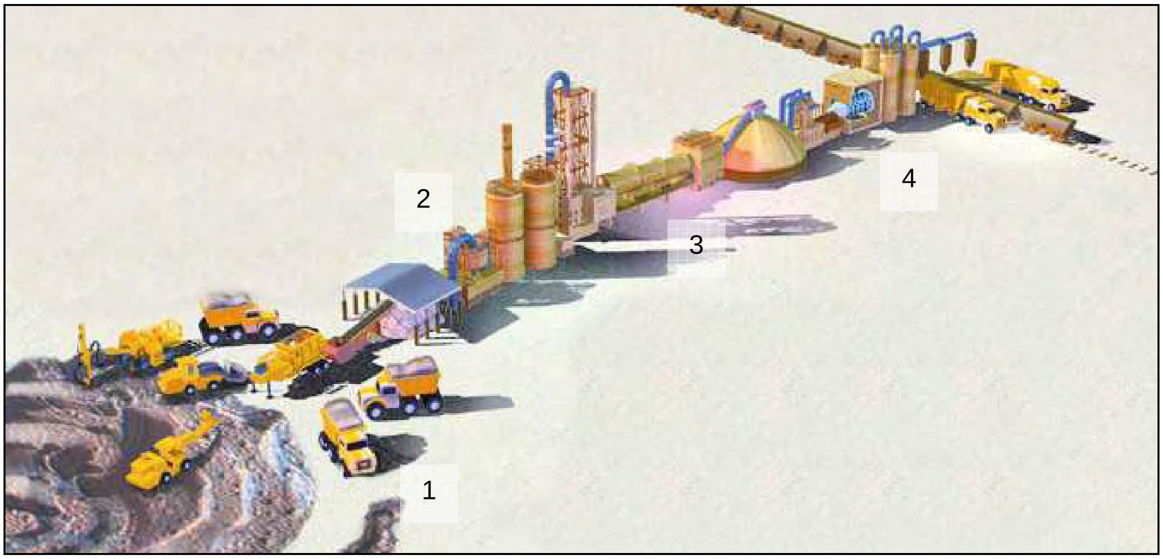

**Figure 1. Steps in the cement manufacturing process: (1) quarry and crush, (2) raw meal preparation, (3) pyroprocess, and (4) finish grind.**

> *Portland Cement is a fine, gray powder that consists of a mixture of the hydraulic cement minerals, tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite, to which one or more forms of calcium sulfate have been added. Portland cement accounts for about 93% of the cement production in the United States. Blended cements are about 2% and masonry cement about 5% of domestic cement production. These cementitious materials also are produced in portland cement plants and contain portland cement as an ingredient.*
>
> *Raw materials are selected, crushed, ground, and proportioned so that the resulting mixture has the desired fineness and chemical composition for delivery to the pyroprocessing system. The major chemical constituents of portland cement are calcium, silicon, aluminum, iron, and oxygen. Minor constituents, generally in a total amount of less than 5% by weight of the mixture, include magnesium, sulfur, sodium, and potassium. And since the raw materials for portland cement come from the*

> *earth's crust, a wide variety of trace elements can be found in the cement, although these generally total less than 1% by weight of the mixture.*
>
> *There are wet-process and dry-process portland cement plants. In the wet process, the ground raw materials are suspended in sufficient water to form a pumpable slurry. In the dry process, they are dried to a flowable powder. New portland cement plants in the United States have exclusively used the dry process because of its lower thermal energy requirement. Thermal energy consumption ranges from about 2.7 to 7.3 million Btu per ton, depending on the age and design of the plant. Average electric energy consumption is about 0.4 million Btu (117 kWh) per ton of cement.*
>
> *The wet process uses rotary kilns exclusively. The dry process also can employ simple rotary kilns. Thermal efficiency can be improved, however, through the use of one or more cyclone-type preheater vessels that are arranged vertically, in series, ahead of the rotary kiln in the material flow path. It can be further improved by diverting up to 60% of the thermal energy (i.e. fuel) required by the pyroprocessing system to a special calciner vessel located between the preheater vessels and the rotary kiln.*
>
> *The rotary kiln is the heart of the portland cement process since the several and complex chemical reactions necessary to produce portland cement take place there. The portland cement kiln is a slightly inclined, slowly rotating steel tube that is lined with appropriate refractory materials. Fuel is supplied at the lower or discharge end of the kiln. Many fuels can be used in the kiln, but coal has predominated in the United States since the mid-1970s. The choice of fuel is based on economics and availability. The hot, gaseous combustion products move countercurrent to the material flow, thereby transferring heat to the solids in the kiln load.*
>
> *The product of the rotary kiln is known as clinker. Heat from just produced clinker is recuperated in a clinker cooling device and returned to the pyroprocess by heating combustion air for the kiln and/or calciner.*
>
> *The cooled clinker is mixed with a form of calcium sulfate, usually gypsum, and ground in ball or tube mills in the finish mill department to produce portland cement. Portland cements are shipped from the packhouse or shipping department in bulk or in paper bags by truck, rail, barge, or ship.*

**Functional unit.** The functional unit, which is the basis for comparison, is a unit mass of portland cement manufactured in the United States from domestically produced clinker. The LCI data in this report are presented in terms of a unit mass of cement in both International System of Units (one metric ton of cement) and U.S. Customary Units (one ton, or 2000 lb, of cement).

The LCI data are presented for each of the four cement plant processes: wet, long dry, dry with preheater, and dry with preheater and precalciner. Although each process is quite different, they all produce the same product, that is, portland cement. Figure 2 shows that there are no significant regional differences to the geographic distribution of cement plant process and capacity (PCA 2005a). Further, there are no significant regional differences in the use of fuel and materials (both type and amount) because these depend on plant process. This figure was created using clinker capacity because neither clinker production nor cement production by state and plant process is published. However, in this figure and for the scope of this LCI, clinker

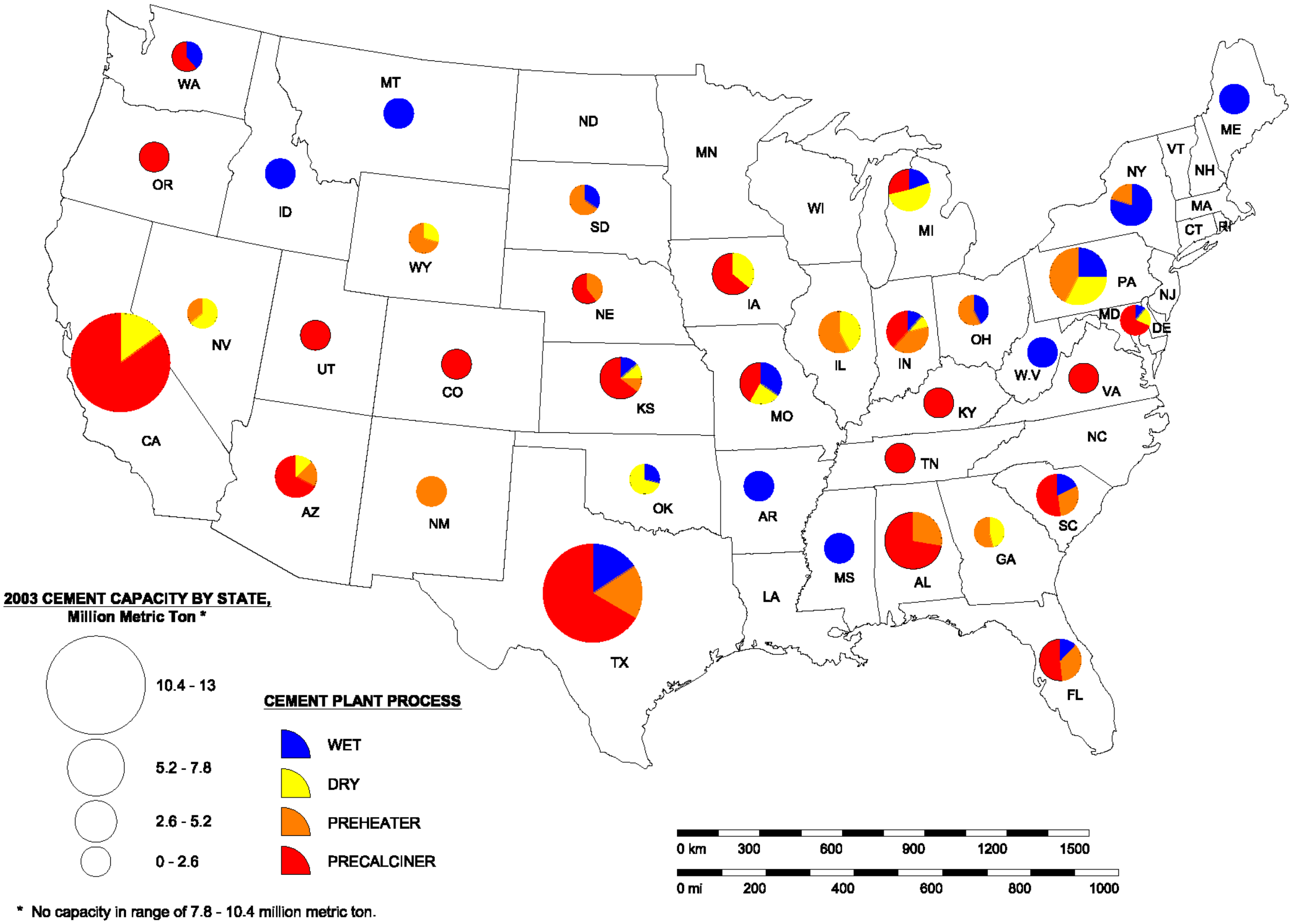

**Figure 2. Clinker capacity by state shows that there are no significant regional differences to the geographic distribution of cement plant process and capacity (PCA 2005a).**

capacity is a reasonable surrogate for cement production because the clinker capacity utilization rate is generally greater than 80% (PCA 2003). Therefore, the LCI results for each process can justifiably be weighted by clinker production to come up with a national average of the four processes. Table 1 shows the amount and percentage of clinker produced from each process. The percentages are used as the weighting factors to calculate weighted averages.

**Table 1. Clinker Production by Process and Weighting Factors (2002 Data)**

| Production | Wet | Long dry | Preheater | Precalciner | Total |
|---|---|---|---|---|---|
| Clinker, metric ton | 12,818,212 | 11,223,607 | 12,285,809 | 41,526,964 | 77,854,592 |
| Percent of total | 16.5% | 14.4% | 15.8% | 53.3% | 100.0% |
| Weighting factor | 0.165 | 0.144 | 0.158 | 0.533 | 1 |

Source: PCA 2005b.

The LCI results refer to an average unit mass of portland cement and not to any specific type of portland cement. The LCI results refer to cement manufactured from domestic clinker. In 2002, domestic clinker comprised 98% of the clinker used to manufacture cement in the United States. That same year, cement manufactured in the United States—some of which was manufactured from imported clinker—comprised 80% of total U.S. cement consumption (van Oss 2002).

**System boundary.** The system boundary, as shown in Figure 3, is chosen to include the four main steps in manufacturing portland cement. It includes the following four steps:

- Quarry and crush: extracting raw material from the earth, crushing to 5-cm (2-in.) pieces, and conveying and stockpiling.
- Raw meal preparation: recovering materials from stockpiles, proportioning to the correct chemical composition, and grinding and blending.
- Pyroprocess: processing raw meal to remove water, calcining limestone and causing the mix components to react to form clinker, cooling and storing the clinker.
- Finish grind: reclaiming the clinker from storage, adding gypsum and grinding to a fine powder, conveying to storage, and shipping in bulk or in bags.

The system boundary also includes transporting all fuel and materials from their source to the cement plant. That is, it includes the emissions, such as from burning fuel in internal combustion engines, to transport the materials to the cement plant. It also includes combustion of fuel in the cement kiln. It generally does not include upstream profiles of producing fuel and electricity. For example, it does not include the energy and emissions associated with extracting coal or generating electricity. One exception is noted in the “Information Sources, Transportation” section.

The ISO 14041 guidelines (ISO 1998) suggest that energy and material flows that do not constitute a significant portion of intermediate or final products need not be included in the LCI if they have a negligible environmental impact. Thus, the energy, materials, and emissions associated with building a cement plant and operating plant buildings are not included in this LCI.

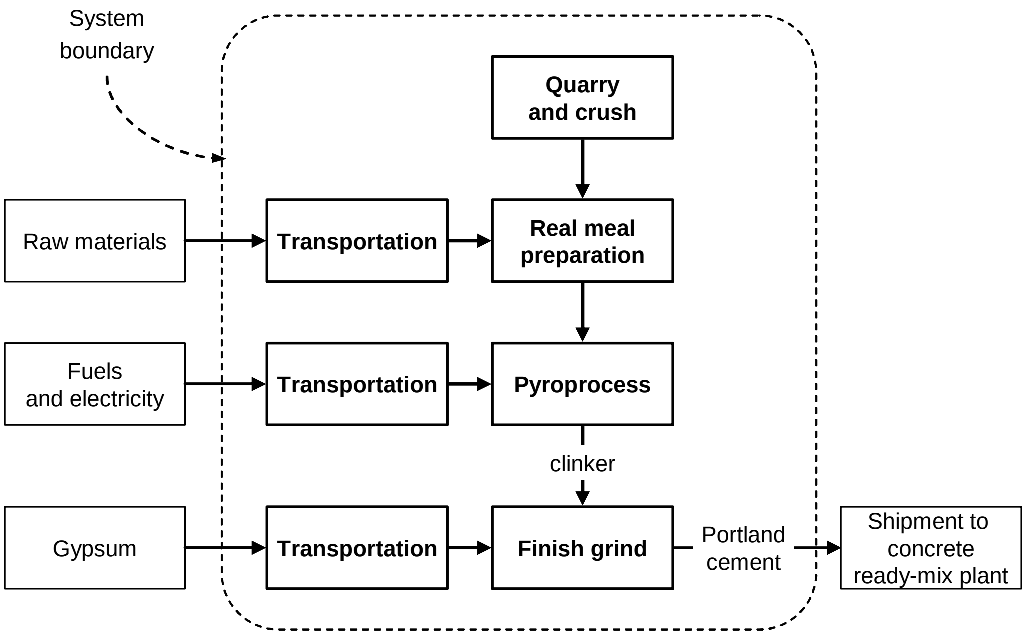

**Figure 3. The system boundary of cement manufacturing defines the limits of the life cycle inventory.**

**Allocation to process steps.** Data on fuel and electricity consumption are readily available for the cement manufacturing process as a whole. However, some assumptions must be made to allocate aggregated data to the individual process steps. Fuel and electricity consumption are allocated to each of the process steps as indicated in Table 2. Gasoline is used equally in each process step in various equipment. Middle distillates are used mainly by mobile equipment and quarry trucks. Thus, 70% of middle distillate consumption is allocated to the quarry with 10% to each of the other process steps. All other fuels are allocated entirely to the pyroprocess. Electricity consumption by process step varies from plant to plant. For the purpose of this report the distribution shown in Table 2 is used.

**Table 2. Percentage Distribution of Fuel and Electricity Use by Process Step**

| **Fuel and electricity** | **Quarry** | **Raw meal preparation** | **Pyroprocess** | **Finish grind** |
|---|---|---|---|---|
| Gasoline | 25 | 25 | 25 | 25 |
| Middle distillates* | 70 | 10 | 10 | 10 |
| Electricity | 8.5 | 14.1 | 27.9 | 49.5 |
| Coal, petroleum coke, etc.** | 0 | 0 | 100 | 0 |
| **Total** | **100** | **100** | **100** | **100** |

*Middle distillates include diesel oil and light fuel oil.
**The other fuels are liquefied petroleum gas, natural gas, residual oil, and various wastes.

## Information Sources

The primary sources of information are PCA’s annual Labor-Energy Survey and the associated quinquennial supplemental survey, which was designed to collect data for the LCI of portland cement. These surveys contain detailed data on the use of raw materials, water, fuel and electricity, and transportation modes and distances.

**Fuel and electricity.** Data on fuel and electricity use and heating value[1] are primarily from *U.S. and Canadian Labor-Energy Input Survey 2002* (PCA 2005b) with additional information from the U.S. Geological Survey (van Oss 2002). Energy consumption is based on survey responses representing approximately 94% of U.S. cement production (PCA 2005b and van Oss 2002). All four cement plant processes are well-represented in this sample, and this sample is large enough to represent manufacturers not included in the survey.

**Raw materials.** Data on raw material use are from *U.S. Environmental R&D Project Questionnaire – 2000 Plant Data* (PCA unpublished). Average raw material consumption is based on the results from 133 kilns of which 36 are wet process, 43 are long dry process, 20 are dry process with preheater, and 34 are dry process with preheater and precalciner. These 133 kilns represent 66% of the 201 in operation in 2000. The amount of raw material accounted for in this sample is an estimated 70% of the total raw material used in cement plants in 2000 (PCA unpublished and van Oss 2000). Detailed data on water use also were reported by half of the plants that participated in answering the questionnaire.

**Transportation.** Data on transportation modes and distances for fuels and raw materials are from *U.S. Environmental R&D Project Questionnaire – 2000 Plant Data* (PCA unpublished). Table 3 shows the percentage of fuels and materials transported by the various modes. Table 4 shows the various transportation distances for each mode. Generally, about 90% of raw materials (limestone, cement rock, marl, shale, slate, and clay) are quarried on-site and transported short distances by road and conveyor. Less than 10% of quarried raw materials (such as sand, slate, and iron ore) is quarried off-site and transported longer distances primarily by barge and rail. About 10% of raw materials are primarily post-industrial waste materials and are transported a range of distances by a variety of modes. Transportation energy conversion factors from Franklin Associates are used to calculate the energy to transport fuel and material to the plant (Franklin 1998). These factors, summarized in Table 5, include precombustion energy for fuel acquisition.

**Table 3. Percentage of Fuel and Material Transportation by Mode***

| Fuel or material | Barge | Road | Rail | Conveyor | Pipeline |
|---|---|---|---|---|---|
| Quarried raw material | 4 | 42 | <1 | 54 | 0 |
| Post-industrial raw material | 11 | 78 | 12 | 0 | 0 |
| Solid fuel | 18 | 35 | 48 | 0 | 0 |
| Liquid fuel | 0 | 99 | <1 | 0 | 1 |
| Natural gas | 0 | 0 | 0 | 0 | 100 |
| Liquid waste fuel | 0 | 93 | 7 | 0 | 0 |
| Solid waste fuel | 1 | 65 | 34 | 0 | 0 |

*Data may not add to 100% due to independent rounding.

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[1] Heating value is used to convert units of fuel and electricity—such as mass, volume, or kW—to units of energy. Higher heating values are used throughout this report. Higher heating value includes the latent heat of vaporization and is determined when water vapor in the fuel combustion products is condensed (ASHRAE 2005).

**Table 4a. Transportation Distances* (SI Units – km)**

| Fuel or material | Barge | Road | Rail | Conveyor | Pipeline |
|---|---|---|---|---|---|
| Quarried raw material | 188 | 25 | 660 | 2 | 0 |
| Post-industrial raw material | 3,320 | 197 | 533 | 0 | 0 |
| Solid fuel | 668 | 249 | 839 | 0 | 0 |
| Liquid fuel | 0 | 62 | 61 | 0 | 370 |
| Natural gas | 0 | 0 | 0 | 0 | 852 |
| Liquid waste fuel | 0 | 235 | 241 | 0 | 0 |
| Solid waste fuel | 518 | 243 | 742 | 0 | 0 |

*One-way transportation.

**Table 4b. Transportation Distances* (U.S. Customary Units – miles)**

| Fuel or material | Barge | Road | Rail | Conveyor | Pipeline |
|---|---|---|---|---|---|
| Quarried raw material | 117 | 15 | 410 | 1 | 0 |
| Post-industrial raw material | 2,064 | 123 | 331 | 0 | 0 |
| Solid fuel | 415 | 155 | 522 | 0 | 0 |
| Liquid fuel | 0 | 38 | 38 | 0 | 230 |
| Natural gas | 0 | 0 | 0 | 0 | 529 |
| Liquid waste fuel | 0 | 146 | 150 | 0 | 0 |
| Solid waste fuel | 322 | 151 | 461 | 0 | 0 |

*One-way transportation.

**Table 5. Transportation Energy Conversion Factors**

| Mode and fuel | Energy consumption* |
|---|---|
| Barge (average of middle distillates and residual oil) | 323 kJ/metric ton-km (447 Btu/ton-mile) |
| Rail (middle distillates) | 270 kJ/metric ton-km (374 Btu/ton-mile) |
| Road (tractor-trailer, middle distillates) | 1,060 kJ/metric ton-km (1,465 Btu/ton-mile) |

*Includes precombustion energy for fuel acquisition.

**Emissions.** Data on emissions come from a variety of sources. The sources and their reference are shown in Table 6. Some emissions are calculated from test results and published emission factors. These are shown in Table 7. Data on emissions are described in more detail in the results section under “Emissions to Air, Land, and Water.” Quarry overburden is often used in quarry reclamation, so there is essentially no generation of solid waste associated with quarries. A small sample of companies indicates that the total amount of ancillary materials, such as refractory brick and grinding media, averages less than 0.5% of the total mass being processed. The majority of these materials are recycled or incorporated into the product and do not result in solid waste releases to the environment. More information from the sample is described in the “Material Inputs, Ancillary Materials” section.

**Table 6. Sources of Information on Emissions**

| Source of emission | Source and reference |
|---|---|
| Transportation | Franklin Associates (Franklin 1998) |
| Mobile equipment | |
| Unpaved roads | National Stone Association (Richards and Brozell 1996) |
| Quarry operations | U.S. EPA emission factors (EPA 2004a) |
| Raw meal preparation | U.S. EPA emission factors (EPA 1995) |
| Finish grinding | |
| Pyroprocess | |
| Non-$CO_2$ | U.S. EPA emission factors (EPA 1995), stack test results (Richards 1996) |
| Fuel $CO_2$ | Calculated (EPA 2004b) |
| Calcination $CO_2$ | Calculated (WBCSD 2005) |
| Hazardous air pollutants | Stack test results (Richards 1996) |
| Solid waste | Innovations in Portland Cement Manufacturing (Bhatty and others 2004) |

**Table 7. Calculated $CO_2$ Emission Factors from Calcination and Waste Combustion**

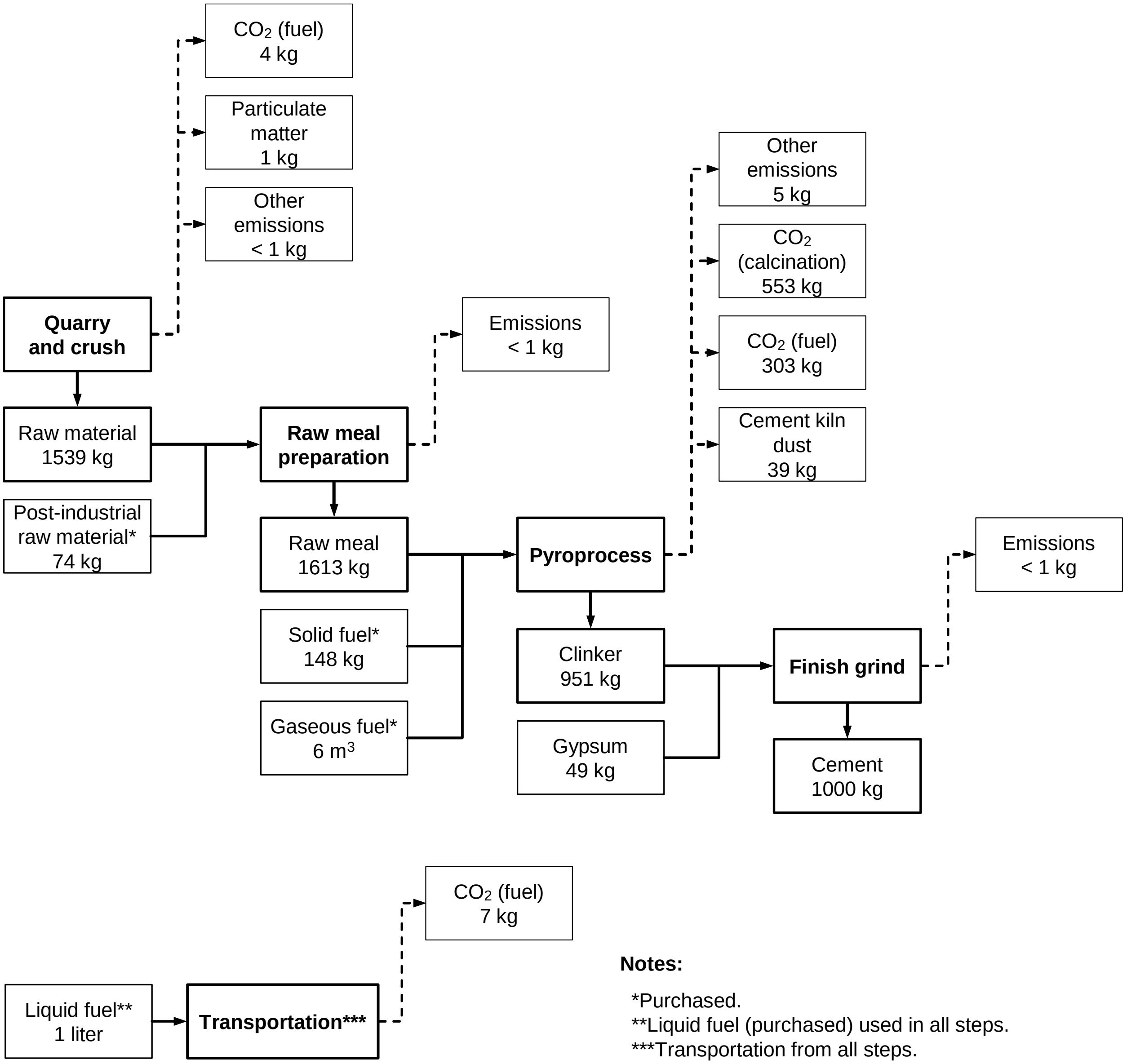
| Process | Assumption |
|---|---|
| Calcination data* | |
| $CaCO_3$ content of raw meal | 78% |
| $CO_2$ in $CaCO_3$ | 44% |
| $CO_2$ emission rate | 0.343 kg/kg raw meal (0.343 lb/lb) |
| Waste combustion** | |
| Carbon content of waste | 57% |
| Heat content (high heat) of waste | 33.2 GJ/metric ton (28.5 MBtu/ton) |
| Ratio of mass of $CO_2$ to carbon | 3.667 |
| $CO_2$ emission rate | 63.0 kg/GJ (147 lb/MBtu) |

*Source: WBCSD 2005.
**Source: PCA unpublished.

## Calculation Methodology

The cement manufacturing process is linear and results in a single product; therefore, there are no product allocation issues to be addressed, and all inputs and emissions are attributed to the product. The LCI results are calculated using linked electronic spreadsheets. The fuel, energy, and material inputs and emissions are compiled and calculated for each cement plant process. These data are then weighted by the relative fraction of clinker produced in each process. The resulting average represents the LCI of an average unit mass of cement manufactured in the United States from domestically produced clinker.

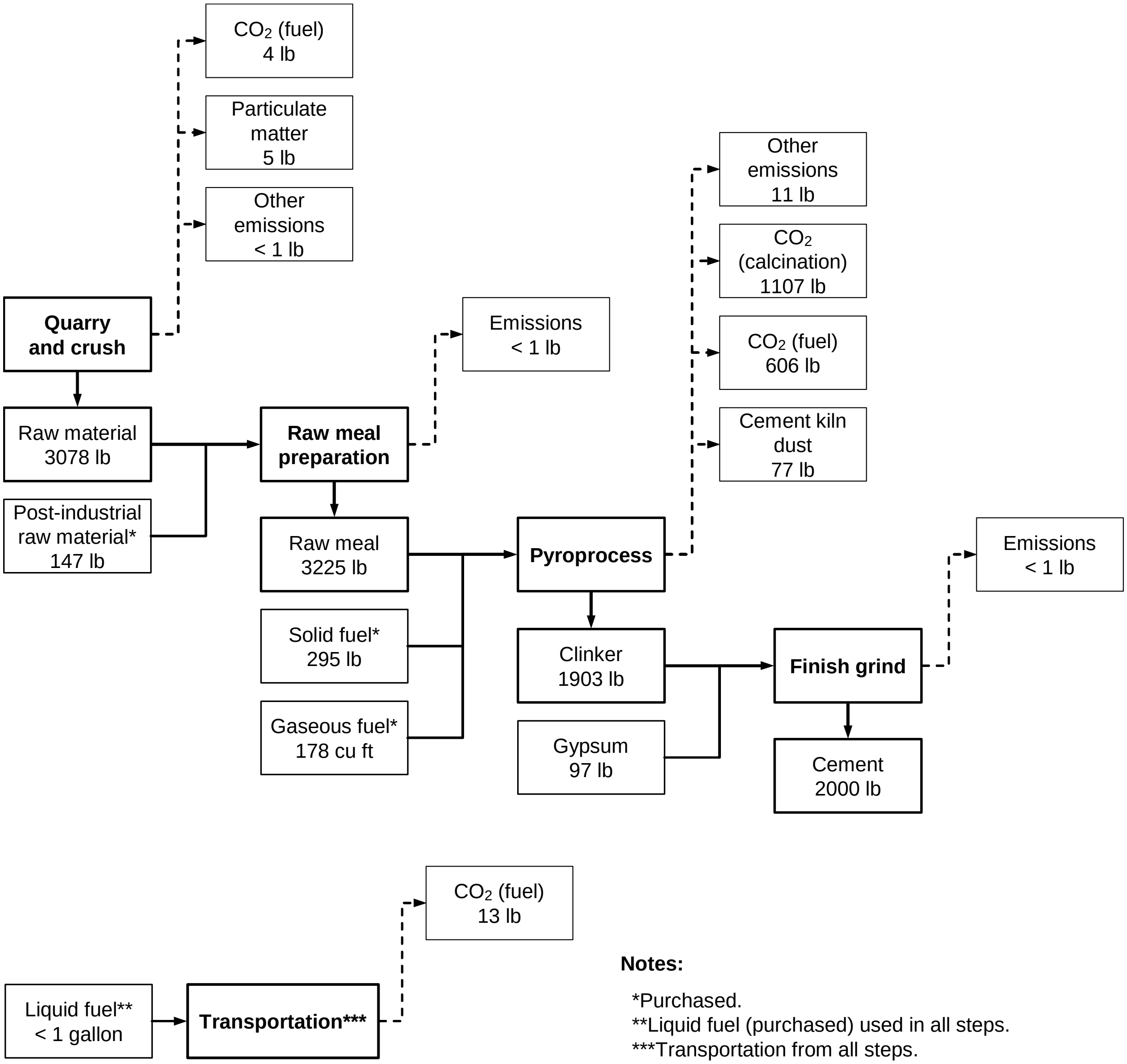
The mass balance of the weighted average process, not including combustion air, is shown in Figure 4. Process losses in the quarrying and raw meal preparation stages are small. They consist mainly of dust from fugitive and controlled point sources. Water added to make raw meal slurry in the wet process is evaporated in the pyroprocess step. Calcining calcium carbonate in the pyroprocess step results in a loss of $CO_2$ of approximately 34% of the mass of raw meal being processed. Some plants, because of chemical or physical limitations, are unable to recycle through the kiln all the dust captured in the kiln dust control equipment. Cement kiln dust (CKD) losses are approximately 4% of the finished product.



**Notes:**

*Purchased.
**Liquid fuel (purchased) used in all steps.
***Transportation from all steps.

**Figure 4a. Weighted average mass balance in the cement manufacturing process (SI Units). This figure is simplified and does not include the mass of combustion air.**



**Notes:**

*Purchased.
**Liquid fuel (purchased) used in all steps.
***Transportation from all steps.

**Figure 4b. Weighted average mass balance in the cement manufacturing process (U.S. Customary Units). This figure is simplified and does not include the mass of combustion air.**

## INVENTORY ANALYSIS – RESULTS

In the tables that follow, results are shown for each of the four cement plant processes and for the average of all processes weighted according to clinker production by process.

### Material Inputs

Material inputs are divided into two groups: (1) primary materials that contribute directly to the process or product performance, such as limestone and coal, and (2) ancillary materials that are used in the process but have only a minor, if any, contribution to the process or product performance, such as refractory and grinding media. Although water does not contribute to the product, it is considered a primary material because it is used in significantly large quantities.

**Primary materials.** The primary input quantities show good agreement with the quantities calculated using the standard assumptions of a raw meal to clinker ratio of 1.6 to 1 and a clinker to cement ratio of 0.95 to 1. The weighted average of the total raw meal consumed is 1,613 kg/metric ton (3,225 lb/ton) of cement for each process. As shown in Table 8, the average input for all processes is 6.1% above the calculated quantity. Therefore, LCI results related to raw materials will tend to be slightly overestimated in this report.

**Table 8. Comparison of Actual and Calculated Quantities of Raw Meal**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Data source** | **kg/metric ton of cement** | | | | |
| Survey | 1,752 | 1,611 | 1,492 | 1,605 | 1,613 |
| Calculated | 1,520 | 1,520 | 1,520 | 1,520 | 1,520 |
| **Difference, %** | **15%** | **6.0%** | **-1.8%** | **5.6%** | **6.1%** |

The quantities of raw material inputs for each of the four cement plant processes are summarized in Table 9. At any particular cement plant, other raw material may consist of one or more of the following: alkali, alumina catalyst, alumina tailings, bauxite, CHAT, catalytic cracking fines, celite, ceramic chips, diatomite, dolomite, FCC, fine dust, fullers earth, glycol, grinding aide, Hydrophobe, iron colored pigment, laterite, lime, mill scale, pozzolan, recycled glass, quartz, sandblast grit, silica, sodium sesquicarbonate, sugar, Ultra Plas, and, volcanics. Inputs by process step for the four processes are documented in Appendices A through D.

**Table 9a. Raw Material Inputs by Process Type (SI Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Cement raw material** | **kg/metric ton of cement** | | | | |
| Limestone | 1,228 | 1,262 | 1,137 | 1,127 | 1,165 |
| Cement rock, marl | 269 | 131 | 70 | 249 | 207 |
| Shale | 65 | 13 | 23 | 68 | 52 |
| Clay | 62 | 35 | 100 | 54 | 60 |
| Bottom ash | 10 | 19 | 5 | 9 | 10 |
| Fly ash | 17 | 23 | 7 | 12 | 13 |
| Foundry sand | 0 | 11 | 5 | 3 | 4 |
| Sand | 57 | 36 | 36 | 38 | 40 |
| Iron, iron ore | 9 | 15 | 16 | 14 | 14 |
| Blast furnace slag | 25 | 38 | 34 | 9 | 20 |
| Slate | 7 | 0 | 0 | 0 | 1 |
| Other raw material | 3 | 29 | 59 | 23 | 26 |
| **Total raw meal*** | **1,752** | **1,611** | **1,492** | **1,605** | **1,613** |
| Gypsum, anhydrite | 57 | 42 | 50 | 48 | 49 |
| Water, process | 485 | 0 | 7 | 14 | 88 |
| Water, non-process | 574 | 1,133 | 1,134 | 592 | 752 |

*Data may not add to total shown because of independent rounding.

**Table 9b. Raw Material Inputs by Process Type (U.S. Customary Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Cement raw material** | **lb/ton of cement** | | | | |
| Limestone | 2,455 | 2,523 | 2,273 | 2,255 | 2,329 |
| Cement rock, marl | 538 | 262 | 141 | 499 | 414 |
| Shale | 130 | 26 | 45 | 135 | 104 |
| Clay | 125 | 69 | 200 | 108 | 119 |
| Bottom ash | 20 | 38 | 10 | 18 | 20 |
| Fly ash | 35 | 45 | 15 | 23 | 27 |
| Foundry sand | 0 | 21 | 10 | 5 | 8 |
| Sand | 114 | 72 | 73 | 76 | 81 |
| Iron, iron ore | 17 | 30 | 32 | 28 | 27 |
| Blast furnace slag | 50 | 77 | 68 | 18 | 40 |
| Slate | 14 | 0 | 0 | 0 | 2 |
| Other raw material | 6 | 58 | 118 | 47 | 53 |
| **Total raw meal*** | **3,505** | **3,222** | **2,985** | **3,211** | **3,225** |
| Gypsum, anhydrite | 113 | 85 | 99 | 95 | 97 |
| Water, process | 969 | 0 | 14 | 28 | 177 |
| Water, non-process | 1,148 | 2,266 | 2,267 | 1,183 | 1,505 |

*Data may not add to total shown because of independent rounding.

**Water.** Water use is divided into process water and non-process water. Process water is used to make raw meal slurry in the wet process and in the semi-dry process. However, few plants employ the semi-dry process. Only four plants reported using water for this purpose (PCA unpublished). Non-process water consists of water used for contact cooling (such as water sprayed directly into exhaust gases and water added to grinding mills), non-contact cooling (such as engine or equipment cooling), cement kiln dust landfill slurries, and dust suppression. Water is used to suppress dust on roads, raw material stores, fuel stores, and cement kiln dust piles. A breakdown of non-process water is shown in Table 10.

**Table 10a. Non-process Water Use (SI Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Water** | **kg/metric ton of cement** | | | | |
| Contact cooling water | 4 | 111 | 82 | 73 | 68 |
| Non-contact cooling water | 480 | 791 | 859 | 405 | 544 |
| Road dust suppression | 18 | 25 | 75 | 19 | 28 |
| Non-road dust suppression | 6 | 7 | 7 | 4 | 5 |
| Other Laboratory and grounds | 1 | 0 | 5 | 13 | 8 |
| CKD landfill slurry | 10 | 0 | 0 | 0 | 2 |
| Other | 2 | 94 | < 1 | 24 | 27 |
| **Total*** | **521** | **1,028** | **1,028** | **537** | **682** |

*Data may not add to total shown because of independent rounding.

**Table 10b. Non-process Water Use (U.S. Customary Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Water** | **lb/ton of cement** | | | | |
| Contact cooling water | 8 | 244 | 180 | 161 | 151 |
| Non-contact cooling water | 1,059 | 1,743 | 1,894 | 892 | 1200 |
| Road dust suppression | 40 | 55 | 166 | 41 | 62 |
| Non-road dust suppression | 13 | 16 | 15 | 8 | 11 |
| Other Laboratory and grounds | 2 | 0 | 12 | 29 | 18 |
| CKD landfill slurry | 22 | 0 | 0 | 0 | 4 |
| Other | 4 | 208 | < 1 | 52 | 59 |
| **Total*** | **1,148** | **2,266** | **2,267** | **1,183** | **1,505** |

*Data may not add to total shown because of independent rounding.

**Ancillary materials.** The quantities of ancillary materials in cement manufacturing are shown in Table 11. The data are based on information provided by a small sample of companies representing eight plants (Nisbet 1997). Because these inputs are less than 1% of the total material input and because they make only minor contributions to emissions or residuals, broader sampling to improve data quality was not undertaken.

Some minor differences are observed between the four cement plant processes. Chains are not used in kilns with preheaters or precalciners. The estimate for filter bags in dust collectors is lower in wet kilns because of wet grinding raw materials and because these kilns, being older, are more likely to be equipped with electrostatic precipitators. Refractory consumption in wet kilns is apparently four times greater than in dry kilns probably due to the limited data sample. The majority of these materials are recycled after use as follows:

- Explosives: no residuals, trace emissions.
- Refractory: the majority is recycled into the manufacturing process, some non-chrome brick is landfilled.
- Grinding media: recycled by vendors.
- Grinding aids: 90%-95% retained in cement.

- Filter bags: landfilled or used as fuel.
- Oil and grease: sent to commercial recyclers.
- Solvents: sent to commercial recyclers.
- Cement bags: no on-site residuals.
- Chains: sent to commercial recyclers.

**Table 11a. Ancillary Material Inputs by Process Type (SI units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Ancillary material** | **kg/metric ton of cement** | | | | |
| Explosive | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| Refractory | 1.70 | 0.44 | 0.44 | 0.44 | 0.71 |
| Grinding media | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 |
| Grinding aids | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 |
| Filter bags | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Oil & grease | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| Cement bags | 0.68 | 0.68 | 0.68 | 0.68 | 0.68 |
| Chains | 0.07 | 0.07 | NA | NA | 0.03 |

NA = not applicable.

**Table 11b. Ancillary Material Inputs by Process Type (U.S. Customary Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Ancillary material** | **lb/ton of cement** | | | | |
| Explosives | 0.59 | 0.59 | 0.59 | 0.59 | 0.59 |
| Refractory | 3.40 | 0.88 | 0.88 | 0.88 | 1.42 |
| Grinding media | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 |
| Grinding aids | 0.72 | 0.72 | 0.72 | 0.72 | 0.72 |
| Filter bags | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 |
| Oil & grease | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 |
| Cement bags | 1.36 | 1.36 | 1.36 | 1.36 | 1.36 |
| Chains | 0.13 | 0.13 | NA | NA | 0.05 |

NA = not applicable.

## Energy Input

**Cement manufacturing.** The weighted average energy consumption, including fuel and electricity, is 4.8 GJ/metric ton (4.1 MBtu/ton) of cement. Fossil fuels account for about 80% of the total, and waste fuels and electricity account for about 10% each. The pyroprocess step uses 88% of the total fuel and 91% of the total energy. The remaining fuel is consumed by mobile equipment either in the quarry or in general plant duties.

A heat balance per unit of clinker can be used to check the reasonableness of survey data. For example, Table 12 shows a heat balance per unit of clinker for a wet process kiln. In this case, about 30% of the fuel produces the theoretical heat required by the process and close to

38% of the fuel is used to evaporate the water in the raw meal slurry. The exhaust gases from the kiln and clinker cooler stacks account for 16% of heat losses while radiation from the kiln shell accounts for 12%.

**Table 12a. Heat Balance for a Wet Process Kiln (SI Units)**

| Heat input, MJ/metric ton of clinker | | % | Heat output, MJ/metric ton of clinker | | % |
|---|---|---|---|---|---|
| Combustion of fuel | 5,635.7 | 96.5 | Theoretical heat required | 1,784.2 | 30.5 |
| Sensible heat in fuel | 4.9 | 0.1 | Exit gas losses | 751.8 | 12.9 |
| Organic matter in feed | none | none | Evaporation of moisture | 2,239.5 | 38.3 |
| Sensible heat in feed | 113.8 | 1.9 | Dust in exit gas | 11.3 | 0.2 |
| Sensible heat in cooler air | 75.8 | 1.3 | Clinker discharge | 56.6 | 1.0 |
| Sensible heat in primary air | 9.3 | 0.2 | Cooler stack losses | 189.9 | 3.3 |
| Sensible heat in infiltrated air | 0.00 | 0.0 | Kiln shell losses | 677.7 | 11.6 |
| | | | Calcination of wasted dust | 40.7 | 0.7 |
| | | | Unaccounted losses | 87.8 | 1.5 |
| **Total*** | **5,839.6** | **100.0** | **Total** | **5,839.6** | **100.0** |

Source: Peray 1986.
*Data may not add to total shown because of independent rounding.

**Table 12b. Heat Balance for a Wet Process Kiln (U.S. Customary Units)**

| Heat input, 1,000 Btu/ton of clinker | | % | Heat output, 1,000 Btu/ton of clinker | | % |
|---|---|---|---|---|---|
| Combustion of fuel | 4,845.8 | 96.5 | Theoretical heat required | 1,534.2 | 30.5 |
| Sensible heat in fuel | 4.3 | 0.1 | Exit gas losses | 646.5 | 12.9 |
| Organic matter in feed | none | none | Evaporation of moisture | 1,925.6 | 38.3 |
| Sensible heat in feed | 97.9 | 1.9 | Dust in exit gas | 9.7 | 0.2 |
| Sensible heat in cooler air | 65.2 | 1.3 | Clinker discharge | 48.7 | 1.0 |
| Sensible heat in primary air | 8.0 | 0.1 | Cooler stack losses | 163.3 | 3.3 |
| Sensible heat in infiltrated air | 0.00 | 0.1 | Kiln shell losses | 582.7 | 11.6 |
| | | | Calcination of wasted dust | 35.0 | 0.7 |
| | | | Unaccounted losses | 76.4 | 1.5 |
| **Total*** | **5,021.1** | **100.0** | **Total** | **5,021.1** | **100.0** |

Source: Peray 1986.
*Data may not add to total shown because of independent rounding.

The dry process requires the same theoretical heat but uses considerably less energy to evaporate residual moisture in the kiln feed. In the long dry process, kiln shell losses are similar to those in wet process kilns, but in the preheater process and in the preheater plus precalciner processes the kilns are shorter and shell losses are less. The reduction in kiln shell losses is offset to some extent by an increase in electricity consumption in the preheaters. The theoretical heat output from the various types of cement kilns is shown in Table 13.

**Table 13. Theoretical Heat Output from Cement Kilns**

| Theoretical heat | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| GJ/metric ton clinker | 5.844 | 4.999 | 3.615 | 3.615 | 4.181 |
| Btu/ton clinker | 5.021 | 4.295 | 3.106 | 3.106 | 3.593 |
| GJ/metric ton cement | 5.493 | 4.699 | 3.398 | 3.398 | 3.931 |
| Btu/ton cement | 4.720 | 4.037 | 2.920 | 2.920 | 3.377 |

Source: Peray 1986.

Coal used in cement plants is almost exclusively bituminous coal (Bhatty and others 2004, Fiscor 2001, and van Oss 2002). Only one plant in the survey used lignite coal (PCA unpublished). No distinction is made between bituminous and subbituminous coal in the survey, and no plants use anthracite coal. Further, in this LCI it is a serious error to assume that petroleum coke is equivalent to coke. Petroleum coke, which is a by-product of oil refining, is used in cement plants as a fuel. Coke, which is manufactured from bituminous coal, is not used in cement plants. Table 14 shows fuel and electricity input for each process type.

**Table 14a. Fuel and Electricity Input by Process Type (SI Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Fuel and electricity** | **Fuel or electricity unit/metric ton of cement** | | | | |
| Coal, metric ton | 0.121 | 0.106 | 0.117 | 0.101 | 0.107 |
| Gasoline, liter | 0.348 | 0.049 | 0.106 | 0.097 | 0.133 |
| Liquefied petroleum gas, liter | 0 | 0.0400 | 0.0042 | 0.0148 | 0.0143 |
| Middle distillates, liter | 0.716 | 0.668 | 0.804 | 1.359 | 1.066 |
| Natural gas, $m^3$ | 2.067 | 5.329 | 3.754 | 7.253 | 5.569 |
| Petroleum coke, metric ton | 0.0326 | 0.0528 | 0.0139 | 0.0134 | 0.0223 |
| Residual oil, liter | 0.0181 | 0.0548 | 0.000 | 0.0624 | 0.0442 |
| Wastes, metric ton | 0.0634 | 0.0080 | 0.0037 | 0.0103 | 0.0177 |
| Electricity, kWh | 137 | 150 | 150 | 143 | 144 |

Source: PCA 2005b.

**Table 14b. Fuel and Electricity Input by Process Type (U.S. Customary Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Fuel and electricity** | **Fuel or electricity unit/ton of cement** | | | | |
| Coal, ton | 0.121 | 0.106 | 0.117 | 0.101 | 0.107 |
| Gasoline, gallon | 0.0834 | 0.0118 | 0.0255 | 0.0233 | 0.0319 |
| Liquefied petrol. gas, gallon | 0 | 0.0096 | 0.0010 | 0.0035 | 0.0034 |
| Middle distillates, gallon | 0.171 | 0.160 | 0.193 | 0.326 | 0.255 |
| Natural gas, 1000 $ft^3$ | 0.066 | 0.171 | 0.120 | 0.232 | 0.178 |
| Petroleum coke, ton | 0.0326 | 0.0528 | 0.0139 | 0.0134 | 0.0223 |
| Residual oil, gallon | 0.0043 | 0.0131 | 0 | 0.0150 | 0.0106 |
| Wastes, ton | 0.0634 | 0.0080 | 0.0037 | 0.0103 | 0.0177 |
| Electricity, kWh | 125 | 136 | 136 | 130 | 131 |

Source: PCA 2005b.

Fuel and electricity expressed in terms of process energy per unit of cement, as shown in Table 15, reflect the relative thermal efficiencies of the four process types. In 55% of plants, post-consumer or post-industrial wastes (or both) are used as fuel. Of those using waste fuel, the types used are: tire-derived wastes (in 69% of plants), waste oil (in 16% of plants), solvents (in 24% of plants), other solid wastes (in 22% of plants), and other wastes (in 12% of plants). Some plants use more than one type of waste fuel (PCA unpublished).

**Table 15a. Energy Inputs by Process Type (SI Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Energy source** | **GJ/metric ton of cement** | | | | |
| Coal | 3.165 | 2.780 | 3.064 | 2.658 | 2.823 |
| Gasoline | 0.0121 | 0.0017 | 0.0037 | 0.0034 | 0.0046 |
| Liquefied petroleum gas | 0 | 0.0011 | 0.0001 | 0.0004 | 0.0004 |
| Middle distillates | 0.0277 | 0.0258 | 0.0311 | 0.0526 | 0.0412 |
| Natural gas | 0.0786 | 0.203 | 0.143 | 0.276 | 0.212 |
| Petroleum coke | 1.145 | 1.850 | 0.488 | 0.471 | 0.783 |
| Residual oil | 0.0008 | 0.0023 | 0 | 0.0026 | 0.0018 |
| Wastes | 1.476 | 0.187 | 0.087 | 0.240 | 0.412 |
| Electricity | 0.495 | 0.541 | 0.540 | 0.517 | 0.520 |
| **Total** | **6.400** | **5.591** | **4.357** | **4.220** | **4.798** |

Source: PCA 2005b.

**Table 15b. Energy Inputs by Process Type (U.S. Customary Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Energy source** | **MBtu/metric ton of cement** | | | | |
| Coal | 2.719 | 2.388 | 2.633 | 2.283 | 2.425 |
| Gasoline | 0.0104 | 0.0015 | 0.0032 | 0.0029 | 0.0040 |
| Liquefied petroleum gas | 0 | 0.0009 | 0.0001 | 0.0003 | 0.0003 |
| Middle distillates | 0.0238 | 0.0222 | 0.0267 | 0.0452 | 0.0354 |
| Natural gas | 0.0676 | 0.174 | 0.123 | 0.237 | 0.182 |
| Petroleum coke | 0.983 | 1.590 | 0.419 | 0.404 | 0.673 |
| Residual oil | 0.0006 | 0.0020 | 0 | 0.0022 | 0.0016 |
| Wastes | 1.269 | 0.161 | 0.075 | 0.206 | 0.354 |
| Electricity | 0.425 | 0.465 | 0.464 | 0.444 | 0.447 |
| **Total** | **5.499** | **4.804** | **3.743** | **3.626** | **4.122** |

Source: PCA 2005b.

Table 16 shows the percentage contribution of each of the energy sources. Gasoline, liquefied petroleum gas, middle distillates, and residual oil each contribute less than 1% of total energy input.

**Table 16. Percent Contribution by Source of Energy Inputs by Process Type**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Energy source** | **Percent contribution by source** | | | | |
| Coal | 49.5 | 49.7 | 70.3 | 63.0 | 60.0 |
| Gasoline | 0.2 | < 0.1 | 0.1 | 0.1 | 0.1 |
| Liquefied petroleum gas | 0.0 | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| Middle distillates | 0.4 | 0.5 | 0.7 | 1.2 | 0.9 |
| Natural gas | 1.2 | 3.6 | 3.3 | 6.5 | 4.7 |
| Petroleum coke | 17.9 | 33.1 | 11.2 | 11.2 | 15.4 |
| Residual oil | < 0.1 | < 0.1 | 0.0 | 0.1 | < 0.1 |
| Wastes | 23.1 | 3.3 | 2.0 | 5.7 | 7.6 |
| Electricity | 7.7 | 9.7 | 12.4 | 12.2 | 11.2 |
| **Total*** | **100.0** | **100.0** | **100.0** | **100.0** | **100.0** |

Source: PCA 2005b.
*Data may not add to total shown because of independent rounding.

The energy input data indicate the expected differences in quantities used in the wet and dry processes. The differences in fuel mix between the four process types are a function of economics and technology. This is evident from the greater use of wastes in wet process plants as a means of controlling their fuel costs and increasing their competitiveness. Preheater and precalciner kilns consume considerably less petroleum coke because of its higher sulfur content which can lead to blockages in the preheater system. Wet grinding of raw materials contributes to the lower electric power input to the wet process.

**Transportation.** The LCI includes transportation energy for delivering all fuels and raw materials to the plant, except for natural gas, which arrives via pipeline. There is a small amount of double counting of transportation energy for on-site quarried materials because, in addition to using the transportation energy conversion factors from Franklin Associates, some of this energy is reported as fuel use in PCA surveys. However, (1) since the transportation energy conversion factors are applied to one-way trips, (2) the PCA surveys do not include transportation energy for purchased materials, and (3) because transportation energy is a relatively small component of total energy, this double counting is not significant. Average transportation energy is thus 0.091 GJ/metric ton (0.078 MBtu/ton) of cement, which represents approximately 2% of total energy input.

A comparison of the energy used to transport fuels and materials in Table 17 shows that approximately 36% of the transportation energy per unit of cement is used in transporting fuel, primarily coal and petroleum coke.

**Table 17. Percent Distribution of Transportation Energy for Materials by Process Type**

| Transportation energy | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| GJ/metric ton of cement | 0.087 | 0.068 | 0.064 | 0.106 | 0.091 |
| MBtu/ton of cement | 0.075 | 0.059 | 0.055 | 0.091 | 0.078 |
| **Percent distribution** | | | | | |
| On-site quarried material | 3.8 | 13.0 | 15.3 | 33.1 | 24.3 |
| Off-site quarried material | 3.3 | 4.1 | 7.9 | 4.8 | 4.8 |
| Post-industrial raw material | 34.8 | 31.2 | 30.1 | 37.0 | 35.3 |
| Fuels | 58.1 | 51.6 | 46.8 | 25.1 | 35.6 |

## Emissions to Air, Land, and Water

Emissions to air from cement manufacturing are due to activities in each of the process steps. Quarrying is a source of particulates resulting from drilling, blasting, loading, and hauling materials generally over unpaved roads. In addition there are the combustion emissions from mobile equipment using diesel fuel. The raw meal preparation and finish milling steps are sources of particulates primarily from conveying, transferring, crushing, and grinding. The pyroprocess is a relatively minor source of particulates but it is the major source of combustion gases and $CO_2$ emissions from calcination of limestone.

**Particulate emissions.** Table 18 shows particulate emission for each of the four processes. Data on particulate emissions from the pyroprocess are from Richards (1996). The U.S. EPA Compilation of Air Pollutant Emission Factors AP-42 is used to calculate clinker cooler emissions. It is assumed that coolers are equipped with fabric filters. Particulate emissions from other plant sources—except for quarry and material stockpiles—also are based on AP-42 factors for cement manufacturing (EPA 1995). Quarry emissions are from AP-42 factors for crushed stone processing (EPA 2004a and EPA 1990).

**Table 18a. Particulate Emissions (SI Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Process step** | **kg/metric ton of cement** | | | | |
| Quarry | 2.284 | 2.025 | 1.870 | 2.108 | 2.088 |
| Transportation* | 0.008 | 0.006 | 0.006 | 0.009 | 0.008 |
| Raw meal preparation | 0.027 | 0.060 | 0.023 | 0.025 | 0.030 |
| Pyroprocess | 0.280 | 0.347 | 0.148 | 0.152 | 0.201 |
| Finish grinding | 0.025 | 0.024 | 0.024 | 0.025 | 0.024 |
| **Total** | **2.624** | **2.462** | **2.071** | **2.318** | **2.350** |

*Transportation of purchased material.

**Table 18b. Particulate Emissions (U.S. Customary Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Process step** | **lb/ton of cement** | | | | |
| Quarry | 4.568 | 4.049 | 3.740 | 4.217 | 4.175 |
| Transportation* | 0.015 | 0.012 | 0.011 | 0.017 | 0.015 |
| Raw meal preparation | 0.054 | 0.120 | 0.046 | 0.050 | 0.060 |
| Pyroprocess | 0.561 | 0.694 | 0.295 | 0.304 | 0.401 |
| Finish grinding | 0.049 | 0.048 | 0.049 | 0.049 | 0.049 |
| **Total** | **5.248** | **4.923** | **4.141** | **4.637** | **4.701** |

*Transportation of purchased material.

The original versions of the cement LCI used the U.S. EPA Aerometric Information Retrieval System (AIRS) Source Classification Code (SCC) emission factor to estimate fugitive dust caused by truck traffic on unpaved quarry haul roads (EPA 1990). This factor was chosen because there was not enough information to permit application of the EPA unpaved haul road equation (EPA 1998).

The AIRS SCC factor for uncontrolled emissions is 15 kilograms of total suspended particulates per vehicle kilometer traveled (52 lb/mile). With an assumed dust control factor of 70% resulting from water sprays, haul road emissions per unit mass of quarried material were considered to be too high. The National Stone Association commissioned a study (Richards and Brozell 1996) whose objective was to review and update the AP-42 unpaved haul road equation. The results of the study are used in this cement LCI. The study conducted tests in three quarries and found that the AP-42 equation overestimated PM-10 (particles with a median mass aerodynamic diameter less than or equal to 10 micrometers) emissions by 2 to 5 times. The test conditions at the quarries were as shown in Table 19.

**Table 19. Test Conditions for Quarry Study of Particulate Emissions**

| Variable | Quarry No. 1 | Quarry No. 2 | Quarry No. 3 |
|---|---|---|---|
| Average silt content, % | 7.39 | 7.35 | 7.49 |
| Average moisture content, % | 6.42 | 4.9 | 5.96 |
| Average truck speed, km/h (mph) | 29.85 (18.55) | 27.15 (16.87) | 27.26 (16.94) |
| Average truck weight, metric ton (ton) | 47.63 (52.50) | 47.63 (52.50) | 47.63 (52.50) |
| Average wind speed, km/h (mph) | 9.24 (5.74) | 8.16 (5.07) | 2.57 (1.60) |
| Average watering interval, hour | 2.97 | 3.98 | 2.29 |
| Water application rates, L/m$^2$ (gallon/yd$^2$) | 0.846 (0.187) | 0.846 (0.187) | 0.846 (0.187) |

Source: Richards and Brozell, 1996.

The results of the tests are shown in Table 20. The measured PM-10 emissions resulted in an average emission factor for the three quarries of 0.29 kg/km (1.04 lb/mile). The emissions are expressed in terms of vehicle-kilometers (or miles) traveled. Multiplying PM-10 by 2.1 (EPA 1995) gives an emission factor for total suspended particulates (TSP) of 0.61 kg/km (2.18 lb/mile). These averages are used in the cement LCI. Results based on such a small sample should not be regarded as representative of all quarry operations. Once better data are available, they can be included in an LCI.

**Table 20. Test Results of Quarry Study of Particulate Emissions**

| | PM-10 emissions | TSP emissions | PM-10 emissions | TSP emissions |
|---|---|---|---|---|
| Test location | kg/vehicle-km traveled | | lb/vehicle-mile traveled | |
| Quarry No. 1 | 0.08 | 0.17 | 0.29 | 0.61 |
| Quarry No. 2 | 0.49 | 1.03 | 1.74 | 3.65 |
| Quarry No. 3 | 0.30 | 0.64 | 1.08 | 2.27 |
| Average | 0.29 | 0.61 | 1.04 | 2.18 |

TSP = total suspended particulates.

**Pyroprocess emissions.** Combustion emissions are mainly from the pyroprocess where kiln fuel accounts for 88% of fuel consumed in the manufacturing process. The remainder of the fuel is used by mobile equipment. Total hydrocarbon emissions from the pyroprocess are based on stack test results (Richards 1996). However, the results do not provide specific data for volatile organic compounds (VOC) and methane ($CH_4$) emissions. Therefore, it is assumed that 50% of the total hydrocarbon can be classified as VOC and 50% as $CH_4$. Carbon dioxide emissions from combustion are calculated from the carbon contents of the kiln fuels (EPA 2004b) and $CO_2$ emissions from calcination are calculated from the proportion of calcium carbonate ($CaCO_3$) in the raw meal (WBCSD 2005). Emissions of $SO_2$, $NO_x$, and CO are calculated from AP-42 factors (EPA 1995). Pyroprocess emissions are shown in Table 21.

Emissions of metals including mercury (Hg) and emissions of HCl, other inorganic pollutants, dioxins and furans, and other organic pollutants are available as AP-42 emission factors (EPA 1995). However, these factors are rated with very low data quality indicators (rated D or E) and often represent a few site-specific results. Since there are insufficient data to establish reliable average values, they have not been included. Instead, emission data for HCl, Hg, and dioxins and furans from a summary of tests on kilns not burning hazardous waste fuels (Richards 1996) are include in Table 21. Dioxins and furans are reported as dioxin toxic equivalent (TEQ). According to the U.S. EPA, hazardous waste burning does not have an impact on formation of dioxins and furans (EPA 1999).

**Table 21a. Pyroprocess Emissions from Fuel Combustion* and Calcination (SI Units)**

| | **Wet** | **Long dry** | **Preheater** | **Precalciner** | **Average** |
|---|---|---|---|---|---|
| **Emission** | **kg/metric ton of cement** | | | | |
| Particulate matter, total | 0.280 | 0.347 | 0.148 | 0.152 | 0.201 |
| Particulate matter, PM-10 | no data | no data | no data | no data | no data |
| Particulate matter, PM-2.5 | no data | no data | no data | no data | no data |
| $CO_2$ | 1,090 | 1,000 | 846 | 863 | 918 |
| $SO_2$ | 3.87 | 4.79 | 0.262 | 0.524 | 1.65 |
| $NO_x$ | 3.49 | 2.88 | 2.28 | 2.00 | 2.42 |
| VOC | 0.0548 | 0.00991 | 0.00304 | 0.0507 | 0.0380 |
| CO | 0.0624 | 0.103 | 0.469 | 1.77 | 1.04 |
| $CH_4$ | 0.0544 | 0.0096 | 0.00269 | 0.0501 | 0.0375 |
| $NH_3$ | 0.00472 | 0.00479 | 0.00475 | 0.00476 | 0.00476 |
| HCl | 0.043 | 0.055 | 0.0013 | 0.065 | 0.0446 |
| Hg | 5.51E-05 | 8.34E-05 | 2.69E-05 | 6.94E-05 | 6.24E-05 |
| Dioxins and furans, TEQ | 6.35E-11 | 3.69E-10 | 2.38E-12 | 6.70E-11 | 9.97E-11 |

*Includes mobile equipment allocated to the pyroprocess step.

**Table 21b. Pyroprocess Emissions from Fuel Combustion* and Calcination (U.S. Customary Units)**

| | **Wet** | **Long dry** | **Preheater** | **Precalciner** | **Average** |
|---|---|---|---|---|---|
| **Emission** | **lb/ton of cement** | | | | |
| Particulate matter, total | 0.561 | 0.694 | 0.295 | 0.304 | 0.401 |
| Particulate matter, PM-10 | no data | no data | no data | no data | no data |
| Particulate matter, PM-2.5 | no data | no data | no data | no data | no data |
| $CO_2$ | 2,180 | 2,000 | 1,691 | 1,726 | 1,835 |
| $SO_2$ | 7.74 | 9.58 | 0.523 | 1.05 | 3.30 |
| $NO_x$ | 6.99 | 5.75 | 4.57 | 4.01 | 4.84 |
| VOC | 0.110 | 0.0198 | 0.00608 | 0.101 | 0.0759 |
| CO | 0.125 | 0.206 | 0.938 | 3.53 | 2.08 |
| $CH_4$ | 0.109 | 0.0193 | 0.00538 | 0.100 | 0.0750 |
| $NH_3$ | 0.00943 | 0.00958 | 0.00950 | 0.00952 | 0.00951 |
| HCl | 0.086 | 0.11 | 0.0026 | 0.13 | 0.089 |
| Hg | 1.10E-04 | 1.67E-04 | 5.38E-05 | 1.39E-04 | 1.25E-04 |
| Dioxins and furans, TEQ | 1.27E-10 | 7.37E-10 | 4.76E-12 | 1.34E-10 | 1.99E-10 |

*Includes mobile equipment allocated to the pyroprocess step.

Fuel combustion emissions from trucks and other equipment at the plant are shown in Table 22. They are calculated by assuming that gasoline and middle distillates are used in mobile equipment and applying Franklin transportation emission factors (Franklin 1998).

**Table 22a. Fuel Combustion Emissions from Plant Mobile Equipment (SI Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Emission** | **kg/metric ton of cement** | | | | |
| Particulate matter, total | 0.00436 | 0.00264 | 0.00342 | 0.00536 | 0.00450 |
| $CO_2$ | 2.72 | 1.93 | 2.43 | 3.93 | 3.20 |
| $SO_2$ | 0.00328 | 0.00292 | 0.00354 | 0.00594 | 0.00469 |
| $NO_x$ | 0.0204 | 0.0172 | 0.0210 | 0.0349 | 0.0277 |
| VOC | 0.00409 | 0.00314 | 0.00389 | 0.00638 | 0.00514 |
| CO | 0.0338 | 0.0190 | 0.0250 | 0.0384 | 0.0327 |
| $CH_4$ | 0.000770 | 0.000533 | 0.000673 | 0.00108 | 0.000887 |

**Table 22b. Fuel Combustion Emissions from Plant Mobile Equipment (U.S. Customary Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Emission** | **lb/ton of cement** | | | | |
| Particulate matter, total | 0.00872 | 0.00528 | 0.00684 | 0.0107 | 0.00899 |
| $CO_2$ | 5.44 | 3.87 | 4.86 | 7.85 | 6.41 |
| $SO_2$ | 0.00657 | 0.00585 | 0.00708 | 0.0119 | 0.00938 |
| $NO_x$ | 0.0409 | 0.0343 | 0.0419 | 0.0697 | 0.0555 |
| VOC | 0.00817 | 0.00628 | 0.00778 | 0.0128 | 0.0103 |
| CO | 0.0675 | 0.0380 | 0.0499 | 0.0769 | 0.0655 |
| $CH_4$ | 0.00154 | 0.00107 | 0.00135 | 0.00216 | 0.00177 |

Fuel combustion emissions from transporting fuel and material are shown in Table 23. They are calculated using transportation mode and distance data (PCA unpublished) and Franklin transportation emission factors (Franklin 1998).

**Table 23a. Emissions from Transportation of Purchased Materials (SI Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Emission** | **kg/metric ton of cement** | | | | |
| Particulate matter, total | 0.00775 | 0.00577 | 0.00573 | 0.00860 | 0.00760 |
| $CO_2$ | 6.20 | 4.89 | 4.54 | 7.64 | 6.52 |
| $SO_2$ | 0.00916 | 0.00732 | 0.00688 | 0.0114 | 0.00974 |
| $NO_x$ | 0.0702 | 0.0460 | 0.0474 | 0.0643 | 0.0599 |
| VOC | 0.00787 | 0.00586 | 0.00630 | 0.00840 | 0.00762 |
| CO | 0.0343 | 0.0268 | 0.0305 | 0.0380 | 0.0346 |
| $CH_4$ | 0.00123 | 0.000965 | 0.00101 | 0.00143 | 0.00126 |

**Table 23b. Emissions from Transportation of Purchased Materials (U.S. Customary Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Emission** | **lb/ton of cement** | | | | |
| Particulate matter, total | 0.0155 | 0.0115 | 0.0115 | 0.0172 | 0.0152 |
| $CO_2$ | 12.4 | 9.78 | 9.09 | 15.3 | 13.0 |
| $SO_2$ | 0.0183 | 0.0146 | 0.0138 | 0.0228 | 0.0195 |
| $NO_x$ | 0.140 | 0.0920 | 0.0948 | 0.129 | 0.120 |
| VOC | 0.0157 | 0.0117 | 0.0126 | 0.0168 | 0.0152 |
| CO | 0.0686 | 0.0537 | 0.0610 | 0.0759 | 0.0691 |
| $CH_4$ | 0.00245 | 0.00193 | 0.00202 | 0.00285 | 0.00252 |

Total emissions of particulates, the major fuel combustion gases, and $CO_2$ from calcination for cement manufacturing are shown in Table 24. The weighted average of $CO_2$ emissions from calcination is approximately 553 kg/metric ton (1,107 lb/ton) or 60% of total $CO_2$ emissions. The $CO_2$ emissions from fuel combustion reflect the fossil fuel efficiency of the four processes. Emissions of $NO_x$ decrease with decreasing fuel consumption. Other combustion gases vary depending on the process.

**Table 24a. Total Emissions to Air (SI units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Emission** | **kg/metric ton of cement** | | | | |
| Particulate matter, total | 2.62 | 2.46 | 2.07 | 2.32 | 2.35 |
| Particulate matter, PM-10 | 0.324 | 0.288 | 0.266 | 0.299 | 0.296 |
| Particulate matter, PM-2.5 | 9.90E-05 | 9.10E-05 | 8.43E-05 | 9.07E-05 | 9.11E-05 |
| $CO_2$ | 1,100 | 1010 | 852 | 874 | 927 |
| $SO_2$ | 3.88 | 4.80 | 0.272 | 0.541 | 1.66 |
| $NO_x$ | 3.58 | 2.94 | 2.35 | 2.10 | 2.50 |
| VOC | 0.0662 | 0.0186 | 0.013 | 0.0648 | 0.0502 |
| CO | 0.125 | 0.146 | 0.521 | 1.84 | 1.10 |
| $CH_4$ | 0.0562 | 0.0111 | 0.00430 | 0.0525 | 0.0395 |
| $NH_3$ | 0.00472 | 0.00479 | 0.00475 | 0.00476 | 0.00476 |
| HCl | 0.043 | 0.055 | 0.0013 | 0.065 | 0.045 |
| Hg | 5.51E-05 | 8.34E-05 | 2.69E-05 | 6.94E-05 | 6.24E-05 |
| Dioxins and furans, TEQ | 6.35E-11 | 3.69E-10 | 2.38E-12 | 6.70E-11 | 9.97E-11 |

**Table 24b. Total Emissions to Air (U.S. Customary Units)**

| | Wet | Long dry | Preheater | Precalciner | Average |
|---|---|---|---|---|---|
| **Emission** | **lb/ton of cement** | | | | |
| Particulate matter, total | 5.25 | 4.92 | 4.14 | 4.64 | 4.70 |
| Particulate matter, PM-10 | 0.648 | 0.575 | 0.531 | 0.598 | 0.593 |
| Particulate matter, PM-2.5 | 1.98E-04 | 1.82E-04 | 1.69E-04 | 1.81E-04 | 1.82E-04 |
| $CO_2$ | 2,200 | 2,010 | 1,700 | 1,750 | 1,850 |
| $SO_2$ | 7.76 | 9.60 | 0.544 | 1.08 | 3.32 |
| $NO_x$ | 7.16 | 5.87 | 4.70 | 4.20 | 5.01 |
| VOC | 0.132 | 0.0372 | 0.0256 | 0.130 | 0.100 |
| CO | 0.249 | 0.293 | 1.04 | 3.68 | 2.21 |
| $CH_4$ | 0.112 | 0.0222 | 0.00859 | 0.105 | 0.0791 |
| $NH_3$ | 0.00943 | 0.00958 | 0.00950 | 0.00952 | 0.00951 |
| HCl | 0.086 | 0.11 | 0.0026 | 0.13 | 0.0891 |
| Hg | 1.10E-04 | 1.67E-04 | 5.38E-05 | 1.39E-04 | 1.25E-04 |
| Dioxins and furans, TEQ | 1.27E-10 | 7.37E-10 | 4.76E-12 | 1.34E-10 | 1.99E-10 |

**Releases to land (solid wastes) and other residuals.** The major waste material from cement manufacturing is CKD. Data on CKD are from Bhatty and others (2004). There is no breakdown of CKD by process type. An industry average of 38.6 kg of CKD is generated per metric ton (93.9 lb/ton) of cement. Of this, 30.7 kg (74.6 lb) are landfilled and 7.9 kg (19.3 lb) are recycled in other applications.

As indicated earlier in the section on ancillary materials, wastes from ancillary materials generally are recycled with little going to landfill. Solid wastes from plant offices and cafeterias are not included in the LCI.

Waste heat is chiefly radiation losses from the kiln and heat contained in exhaust gases from the kiln stack and cooler. The data on heat releases from kiln heat balances indicate that approximately 1.9 GJ/metric ton (1.6 MBtu/ton) waste heat are released with relatively little differences between the four processes. Other releases in the form of noise and vibration are not readily quantifiable and have not been included.

**Releases to water.** Water is used in the raw meal slurry in the wet process and is frequently used to condition or cool kiln exhaust gases before they reach dust control equipment. Water also may be used to cool finish mills. In all these cases the water is evaporated and does not lead to effluents. Water also is used for non-contact cooling—in which case the water does not come into contact with cement or clinker. The main sources of effluents are from non-contact cooling of bearings, and cooling cement directly after the finish mill. Other sources of effluent are water and runoff from plant property storm episodes. Water discharge is shown in Table 25. The location of water discharge is shown in Table 26.

**Table 25a. Water Discharge (SI Units)**

| | Average |
|---|---|
| **Water use, kg/metric ton of cement** | |
| Quarry de-watering | 610 |
| Storm runoff | 304 |
| CKD landfill wells | 1 |
| CKD pile runoff | 11 |
| Other | 80 |
| **Total** | **1,007** |

*Data may not add to total shown because of independent rounding.

**Table 25b. Water Discharge (U.S. Customary Units)**

| | Average |
|---|---|
| **Water use, lb/ton of cement** | |
| Quarry de-watering | 1,345 |
| Storm runoff | 671 |
| CKD landfill wells | 2 |
| CKD pile runoff | 25 |
| Other | 176 |
| **Total** | **2,220** |

*Data may not add to total shown because of independent rounding.

**Table 26. Water Discharge, Percent by Location**

| Water use, lb | Sewer | River | Lake | Process |
|---|---|---|---|---|
| Contact cooling | 51.7 | 0.1 | 19.5 | 28.8 |
| Non-contact cooling | 48.5 | < 0.1 | 50.9 | 0.6 |
| Roadway dust suppression | 88.2 | 3.2 | 3.2 | 5.3 |
| Non-roadway dust suppression | 49.3 | < 0.1 | 47.6 | 3.1 |
| Other laboratory and grounds | 10.9 | 78.2 | 10.8 | 0.0 |

Detailed U.S. data on the composition of liquid effluent are not readily available; however, a small sample of data was obtained from CANMET and others (1993). The data were collected from seven cement plants in the province of Ontario, Canada, over a period of one year, prior to the Ministry of Environment and Energy setting provincial effluent standards for the cement industry. Since North American cement plants have similar operations, this data should be somewhat representative of U.S. cement plants. The data are shown in Table 27.

**Table 27a. Liquid Effluents (SI Units)**

| | Quarrying | Manufacturing | Stormwater |
|---|---|---|---|
| **Liquid effluents** | **kg/metric ton of cement (except for pH)** | | |
| Suspended solids | 9.316E-02 | 1.187E-01 | 7.200E-04 |
| Aluminum | 3.000E-04 | 4.800E-04 | 0 |
| Phenolics | 1.000E-05 | 1.000E-05 | 0 |
| Oil and grease | 2.550E-03 | 4.270E-03 | 0.000E+00 |
| Nitrate, nitrite | 3.930E-03 | 1.410E-03 | 1.000E-05 |
| Dissolved organic compounds | 4.340E-03 | 8.160E-03 | 0 |
| Chlorides | 5.219E-01 | 1.371E-01 | 1.040E-03 |
| Sulfates | 3.038E-01 | 2.536E-01 | 1.050E-03 |
| Sulfides | 5.000E-05 | 1.000E-05 | 0 |
| Ammonia, ammonium | 8.600E-04 | 0 | 0 |
| Phosphorus | 5.000E-06 | 0 | 0 |
| Zinc | 2.000E-05 | 1.000E-05 | 0 |
| pH | 8.21 | 8.3 | 8.84 |

**Table 27b. Liquid Effluents (U.S. Customary Units)**

| | Quarrying | Manufacturing | Stormwater |
|---|---|---|---|
| **Liquid effluents** | **lb/ton of cement (except for pH)** | | |
| Suspended solids | 2.054E-01 | 2.618E-01 | 1.587E-03 |
| Aluminum | 6.614E-04 | 1.058E-03 | 0 |
| Phenolics | 2.205E-05 | 2.205E-05 | 0 |
| Oil and grease | 5.622E-03 | 9.414E-03 | 0.000E+00 |
| Nitrate, nitrite | 8.664E-03 | 3.109E-03 | 2.205E-05 |
| Dissolved organic compounds | 9.568E-03 | 1.799E-02 | 0 |
| Chlorides | 1.151E+00 | 3.022E-01 | 2.293E-03 |
| Sulfates | 6.698E-01 | 5.591E-01 | 2.315E-03 |
| Sulfides | 1.102E-04 | 2.205E-05 | 0 |
| Ammonia, ammonium | 1.896E-03 | 0 | 0 |
| Phosphorus | 1.102E-05 | 0 | 0 |
| Zinc | 4.409E-05 | 2.205E-05 | 0 |
| pH | 8.21 | 8.30 | 8.84 |

## SENSITIVITY

The purpose of this section is to examine the sensitivity of the results of the LCI to underlying assumptions and quality of the data. The LCI results are not sensitive to selection or demarcation of the process steps. The process is linear and there are minimal losses, so all the intermediate product from one step is processed in the subsequent step. An exception is the case of cement ground from imported clinker, which enters the process at the finish grinding step. The overall

LCI of this product can be assumed to be similar to cement made from domestic clinker. It would consist of the upstream profile of the imported clinker plus the LCI of the finish grinding step. However, imported clinker is not considered in this LCI.

## Raw Material Input

Data are aggregated on a national basis. Since the composition of the final product is relatively constant and the same manufacturing technologies are used nationwide, raw material and fuel inputs do not vary significantly on a regional basis.

Raw material composition and raw material input per unit mass of cement are not sensitive to the type of manufacturing process because the four cement manufacturing processes make products meeting the same standards. An exception is process water, which constitutes about 21% by weight of wet process inputs and less than 1% of inputs to the dry process. Ancillary material inputs show very little sensitivity to process types.

## Energy Input

The LCI results are sensitive to the quality of the data on energy consumption in the pyroprocessing step. As Figure 5 indicates, the pyroprocess accounts for an average of about 91% of process energy consumption.

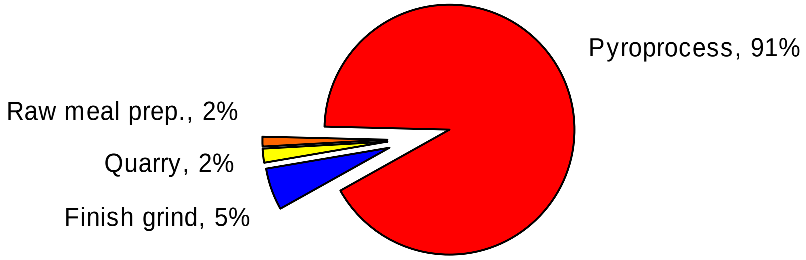


**Figure 5. The pyroprocess step consumes by far the most energy.**

The LCI results are relatively insensitive to transportation distances and transportation mode for purchased materials. The survey data used in this report indicate that transportation energy represents about 2% of total energy input per unit mass of cement.

## Emissions

The majority of combustion gas emissions are a function of the quantity and type of the fuel used in the process. The pyroprocess step consumes approximately 88% of fuel used in the manufacturing process; thus LCI emission results are sensitive to the quality of the data on fuel consumption and fuel mix.

LCI combustion gas emissions are not sensitive to transportation assumptions since the energy used in transportation accounts for about 2% of total energy consumed per unit mass of cement.

Particulate emissions from the pyroprocess and finish grinding steps, as shown in Figure 6, are together about 10% of total emissions from the cement manufacturing process because of air pollution control devices. The majority of particulates emissions are from fugitive sources in quarry operations and materials handling prior to milling in the raw meal preparation step. Most of the particulates in the quarrying step are from unpaved haul roads and wind erosion from stockpiles. The LCI results for particulate emissions are therefore sensitive to assumptions about haul road distances and dust control measures, quantity of material stockpiled, and the accuracy of the relevant emission factors.

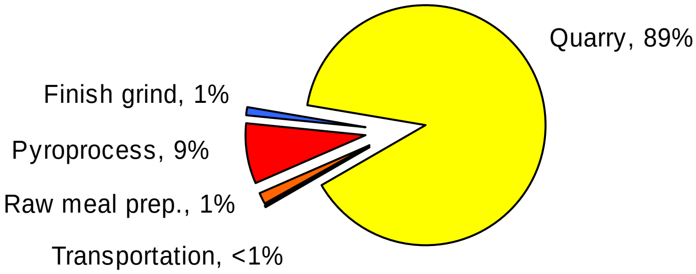


**Figure 6. Quarry operations are responsible for most of the (total) particulate emissions and transportation of purchased material is responsible for the least.**

## REVIEW OF DATA QUALITY AND DATA GAPS

The general data quality requirements include a definition of geographic coverage, meaning the geographical area from which the data are drawn (regional, national, continental, or international). Another general requirement is technology coverage, which defines the technology mix, for example whether it is a weighted average of the actual processes or best available technology. The data should be as current as possible.

The data that have a significant impact on results have a good level of accuracy. A set of industry-standard data-quality indicators complying with ISO 14041 has not yet been developed.

### Material and Energy Input Data

The guidelines proposed by SETAC (1994) include 18 criteria that can be used to give a qualitative assessment of data quality. These criteria are applied to the material and energy input data as shown in Table 28. Furthermore, the quality of the input data is described below according to coverage, currency, representativeness, accuracy, precision, consistency, and reproducibility.

**Table 28. Qualitative Measures of Data Quality for Material and Energy Inputs**

| Criteria | Yes | No | N/A | Comments |
|---|---|---|---|---|
| 1. Are the data from a single production unit or aggregated? If aggregated, how was aggregation done? | | * | | Aggregated from individual production units |
| 2. Is the data source independent? Does the data compiler have a vested interest? | | * | | |
| 3. Is the source of the data reliable? Is it scientifically sound? | * | | | |
| 4. Does the data have currency? Does the age of the data allow them to be used? | * | | | |
| 5. Are the data, their sources and how they have been manipulated well documented? | * | | | |
| 6. Does information on accuracy and errors accompany the data? | * | | | Materials and energy input are compared to calculated inputs |
| 7. Do the data fit entirely within the confines of the boundaries? If not, can the data be partitioned so that they only include those relevant to the LCA? | * | | | |
| 8. Are the data really useful for the purpose of the LCA? | * | | | |
| 9. Do the data contain emission factors? Are they reliable? | | | * | |
| 10. Do the data comply with the laws of thermodynamics and mass balance? | * | | | |
| 11. Have the data ranges for losses in the system been checked? | * | | | |
| 12. Are the energy content data consistent with existing data correlations? | * | | | |
| 13. Have the base calculations and base logic been checked? | * | | | |
| 14. Are the data collected/measured using a broadly accepted test methodology? | * | | | |
| 15. Are there defined data ranges for the data? | | * | | |
| 16. Are the data transparent? Are some data only available in aggregated form to preserve confidentiality? | * | | | A transparent aggregation procedure protects confidentiality |
| 17. Have the data been peer reviewed? | * | | | See VTT (2002) |
| 18. Are the data independently verified? | | * | | |

- Coverage. The data cover the four cement plant processes: wet, long dry, dry with preheater, and dry with preheater and precalciner. Coverage is on a national basis for annual operations. Data from individual plants are aggregated into averages normalized per ton of cement.
- Currency. The data are from 2002 in the case of fuels and electricity, and 2000 for raw material inputs.
- Representativeness. Fuel and electricity inputs are averaged from survey results covering 95% of U.S. cement production. Raw material inputs are based on survey results from 66% of the total number of kilns in operation.

- Accuracy. There is no recognized standard for material inputs or energy consumption by cement kilns. The quantities of primary inputs, raw material, and fuel used in the LCI are consistent with calculated results.
- Precision. There are no recognized standards for the variability of data on cement kilns.
- Consistency. The data have been collected and applied in a consistent manner.
- Reproducibility. The methods of collection, manipulation, and use of the data are documented so that an independent party can reproduce the results.

## Data on Emissions to Air

Emissions of particulates from quarry operation such as blasting, loading, and stockpiling are based on AP-42 factors (EPA 2004a) and are considered to be conservative. Emissions of particulates from haul roads are from an independent study (Richards and Brozell 1996). Emissions from crushing, screening, conveying, and grinding operations are estimated from AP-42 factors whose quality is variable (EPA 1995). Kiln stack emissions of particulate matter, total hydrocarbons, and selected hazardous air pollutants are derived from 1993-1995 test programs (Richards 1996). Test programs, with the exception of data from continuous emission monitors, are of relatively short duration. But, since the test programs are designed to measure emissions during the normal, stable operation of kilns and other equipment, the results are considered to be representative.

Kiln fuel combustion gas emissions of $SO_2$, $NO_x$, and CO and particulate from cooler stack emissions are calculated from AP-42 factors (EPA 1995). $CO_2$ emissions are calculated from carbon content of fuels and $CaCO_3$ content of raw meal (EPA 2004b and WBCSD 2005). Emissions from gasoline- and diesel-fueled vehicles are calculated from peer-reviewed factors (Franklin 1998).

Table 29 shows the application of the SETAC criteria to air emission data. Furthermore, the data quality is described below according to coverage, currency, representativeness, accuracy, precision, consistency, and reproducibility.

- Coverage. The data cover the four cement plant processes: wet, long dry, dry with preheater, and dry with preheater and precalciner. Coverage is on a U.S. national basis and data are derived from test programs and emission factors. Data from individual plants are aggregated into averages normalized to a unit mass basis of cement.
- Currency. Test data are from programs conducted between 1993 and 1996.
- Representativeness. Test data are recorded during the normal stable operations of the kiln and other equipment.
- Accuracy. Test programs use approved methods and comply with the standards of those methods. The accuracy of emission factors is rated in AP-42. The estimates of particulate emissions from sources other than the pyroprocess and unpaved haul roads were developed using AP-42 factors. These may result in conservative estimates.
- Precision. Test data meet the precision requirements of the test procedures.
- Consistency. The data have been collected and applied in a consistent manner.
- Reproducibility. The methods of collection, manipulation, and use of the data are documented so that an independent party can reproduce the results.

**Table 29. Qualitative Measures of Data Quality for Emissions to Air**

| Criteria | Yes | No | N/A | Comments |
|---|---|---|---|---|
| 1. Are the data from a single production unit or aggregated? If aggregated how was aggregation done? |  | * |  | Aggregated from test data or mass balances |
| 2. Is the data source independent? Does the data compiler have a vested interest? | * |  |  | See comments in text. |
| 3. Is the source of the data reliable? Is it scientifically sound? | * |  |  |  |
| 4. Do the data have currency? Does the age of the data allow them to be used? | * |  |  |  |
| 5. Are the data, their sources and how they have been manipulated well documented? | * |  |  |  |
| 6. Does information on accuracy and errors accompany the data? | * |  |  | Reference is made to source documents of emission factors. |
| 7. Do the data fit entirely within the confines of the LCA boundaries? If not, can the data be partitioned so that they only include those relevant to the LCA? | * |  |  |  |
| 8. Are the data really useful for the purpose of the LCA? | * |  |  |  |
| 9. Do the data contain emission factors? Are they reliable? | * |  |  | Emission factors are primarily AP-42.The quality of the factors is variable. See comments in text. |
| 10. Do the data comply with the laws of thermodynamics and mass balance? | * |  |  |  |
| 11. Have the data ranges for losses in the system been checked? |  |  | * | There are negligible losses in the system except for calcination $CO_2$. |
| 12. Are the energy content data consistent with existing data correlations? | * |  |  |  |
| 13. Have the base calculations and base logic been checked? | * |  |  |  |
| 14. Are the data collected/measured using a broadly accepted test methodology? | * |  |  |  |
| 15. Are there defined data ranges for the data? |  | * |  |  |
| 16. Are the data transparent? Are some data only available in aggregated form to preserve confidentiality? | * |  |  |  |
| 17. Have the data been peer reviewed? | * |  |  | See VTT (2002) |
| 18. Are the data independently verified? |  | * |  |  |

## Data Gaps

The only significant gap concerns effluent composition; however, this is minor compared to other material and energy inputs and emissions to air from cement manufacturing.

## INTERPRETATION - CONCLUSIONS

The LCI of the cement manufacturing process has been carried out according to ISO standards 14040 and 14041. The goal of this cement LCI is to develop accurate data on the inputs and emissions associated with production of cement. These data will be used in the development of LCIs of concrete, concrete products, and concrete structures, which will be used in turn to perform life cycle assessments of concrete structures. Because cement constitutes 7% to 15% of concrete's total mass by weight, using cement LCI data incorrectly as concrete LCI data is a serious error.

The energy data used for cement are from 2002 and are national in scope. They include the four main technologies: wet kilns, long dry kilns, dry kilns with preheater, and dry kilns with preheater and precalciner. The data are reported from plants representing approximately 95% of U.S. cement production and have been collected annually for 25 years. We believe these data have a good level of accuracy but have not developed quantitative indicators of data quality. A set of industry standard data quality indicators complying with ISO 14041 has not yet been developed. Air emissions are based largely on U.S. EPA AP-42 emission factors for which qualitative quality indicators are available.

The LCI data and results have been peer reviewed by the PCA membership. The previous version of this report (Nisbet and others 2002) was peer-reviewed by VTT, Finland (Häkkinen and Holt, 2002). The authors "found that the report is a careful study on the environmental aspects of portland cement and that it properly uses the life cycle approach in accordance with the framework described in ISO 14040 and ISO 14041." The LCI contains a set of internally consistent calculations generated by a transparent and fully referenced input/output model. The results of the LCI readily can be updated to accommodate new input or emission data or modified assumptions.

Data used in the cement manufacturing LCI are based on industry-wide surveys of energy consumption, raw material use, and transportation distances. Emissions are calculated using test data and U.S. EPA emission factors.

## ACKNOWLEDGEMENTS

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# APPENDIX – DESCRIPTION OF PORTLAND CEMENT MANUFACTURING PROCESS

PCA R&D Serial No 2467

# Air Pollution Engineering Manual

## Second Edition

AIR & WASTE MANAGEMENT
ASSOCIATION
SINCE 1907

Edited by
Wayne T. Davis

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## PORTLAND CEMENT

Walter L. Greer, Ann Dougherty, and Douglas M. Sweeney

### INTRODUCTION

Portland cement is a fine, gray powder that consists of a mixture of the hydraulic cement minerals, tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite, to which one or more forms of calcium sulfate have been added. Portland cement accounts for about 93% of the cement production in the United States. Blended cements are about 2% and masonry cement about 5% of domestic cement production. These cementitious materials are also produced in portland cement plants and contain portland cement as an ingredient.

Portland, blended, and masonry cements are produced in several different types or formulations for specific purposes or properties. Chemical and physical specifications for the types of portland and masonry cements are written by several agencies, of which the most widely used are those provided by the American Society for Testing and Materials. The most common types of portland cement are designated by the Roman numerals I through V. Blended cements usually have a letter designation following a Roman numeral to indicate the nature of the blend (i.e., Type I-P for a general purpose portland–pozzolan blend). Types of masonry cement are designated by the letters N, S, and M.

The production of portland cement is a four-step process: (1) acquisition of raw materials, (2) preparation of the raw materials for pyroprocessing, (3) pyroprocessing of the raw materials to form portland cement clinker, and (4) grinding of the clinker to portland cement. In a portland cement plant, the pyroprocessing operation is almost always the limiting factor for productive capacity. Figure 1 is a basic flow diagram of the portland cement process. Figure 2 presents a layout of a cement plant recently built in the United States, and Figure 3 shows another modern cement plant. While the various unit operations and unit processes in portland cement plants accomplish the same end result, no single flow diagram can fully represent all plants. Each plant is unique in layout and appearance owing to variations in climate, location, topography, raw materials, fuels, and preferences of equipment vendors and owners. These plants are capital intensive. In 1997, there were 105 plants in the United States producing approximately 76 million tons of portland cement. Portland cement plants can run 24 hours per day for extended periods, for example, six months or more with only minor downtime for maintenance is not unusual.

Raw materials are selected, crushed, ground, and proportioned so that the resulting mixture has the desired fineness and chemical composition for delivery to the pyroprocessing system. The major chemical constituents of portland cement are calcium, silicon, aluminum, iron, and oxygen. Carbon is a major constituent of the cement raw mix, but that element is eliminated during processing. Minor constituents, generally in a total amount of less than 5% by weight of the mixture, include magnesium, sulfur, sodium, and potassium. And since raw materials for portland cement usually come from the earth's crust, a wide variety of trace elements can be found in the cement, although these generally total less than 1% by weight of the mixture. Some of these naturally occurring trace elements can affect the performance of portland cement and/or appear in particulate emissions and process residues from cement plants. Most often, however, they harmlessly substitute for the four major metals in the crystalline matrix of the portland cement.

The more than 30 raw materials that are known to be used in the manufacture of portland cement can be divided into four categories: lime (calcareous), silica (siliceous), alumina (argillaceous), and iron (ferriferous). Limestone or another form of calcium carbonate ($CaCO_3$) will predominate in the mixture of raw materials. One or more quarries are usually associated with a portland cement plant. The terms slurry, raw meal, raw mix, and kiln feed are synonymous in naming the prepared raw materials or product of the raw mill department. At least 1575 kg (3465 pounds) of dry raw materials are required to produce 1000 kg (2200 pounds) of cement clinker. This ratio of feed to product can increase by several pounds due

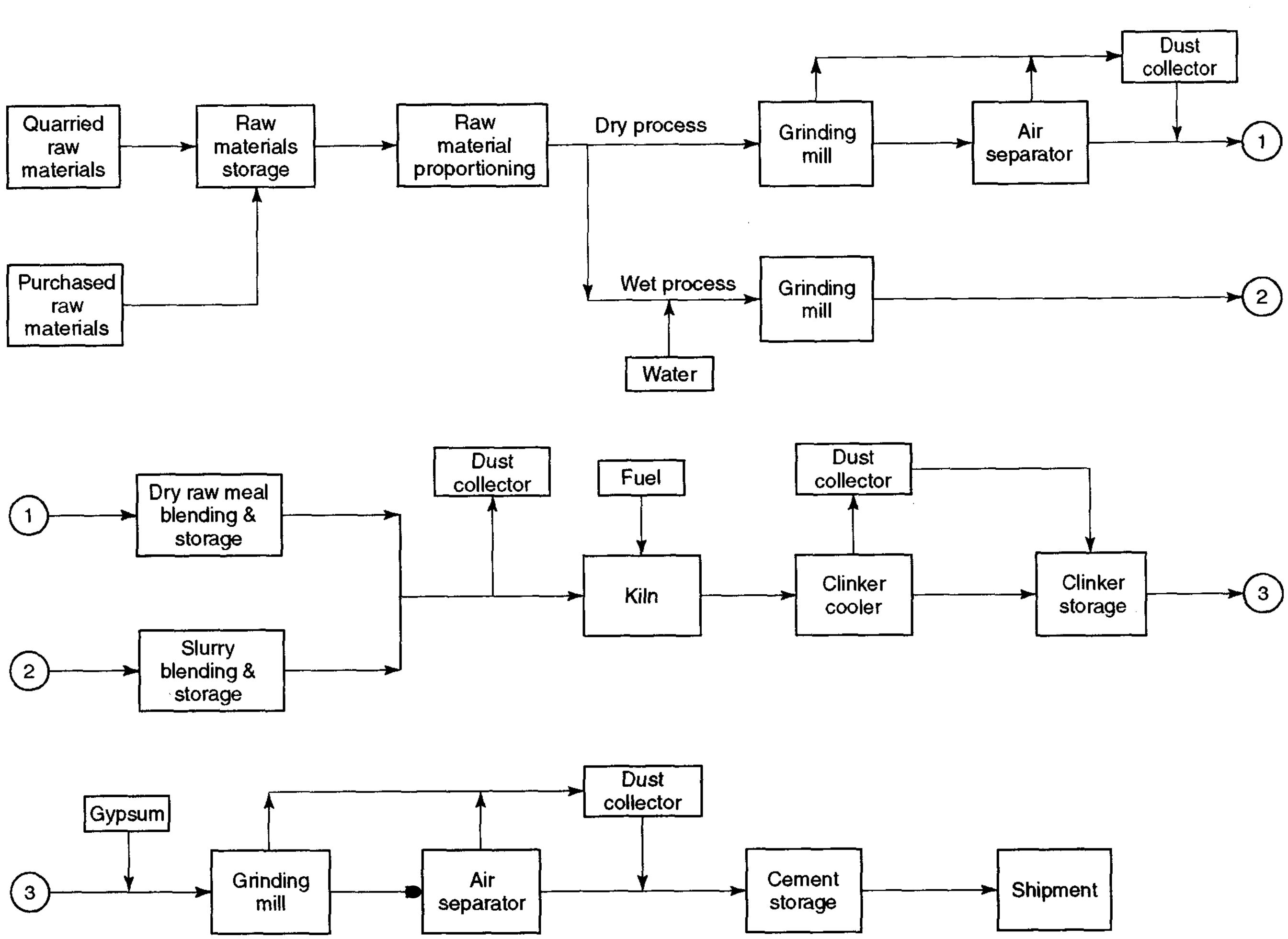

**Figure 1.** Basic Flow Diagram of the Portland Cement Manufacturing Process.

to raw mix composition and dust removal. Most of the weight lost between raw mix and clinker is carbon dioxide ($CO_2$) that is calcined from the $CaCO_3$ and emitted to the atmosphere during pyroprocessing. About one ton of $CO_2$ is emitted per ton of portland cement clinker produced, with about one-half of this amount resulting from the calcination of $CaCO_3$. The balance results from the combustion of fuel. More efficient kilns produce less $CO_2$ per ton of clinker than less efficient kilns. Fuels containing hydrogen (e.g., natural gas) result in lower $CO_2$ emissions than coal or petroleum coke.

Standard industry practice is to report the chemical analyses of raw materials, process intermediates, by-products, and portland cement as metal oxides, even though the constituents are rarely present in that form. If desired, the theoretical quantities of minerals in the cement matrix are calculated from the oxide analysis using specified formulas. Actual quantities of minerals may be determined by X-ray diffraction.

There are wet-process and dry-process portland cement plants. In the wet process, the ground raw materials are suspended in sufficient water to form a pumpable slurry. In the dry process, they are dried to a flowable powder. New portland cement plants in the United States have exclusively used the dry process because of its lower thermal energy requirement. The Portland Cement Association estimated in 1997 that the average thermal energy used to produce a ton of cement in the United States was about 4.0 million Btu. Thermal energy consumption ranged from about 2.7 to 7.3 million Btu per ton, depending on the age and design of the plant. Average electric energy consumption is about 0.4 million Btu (117 kWh) per ton of cement.

The prepared raw materials are fed to one of several pyroprocessing systems in the kiln or burning department. Each system accomplishes the same result via the following basic steps: evaporation of free water, evolution of combined water, calcination of the carbonate constituents (decarbonization), and formation of the portland cement minerals (clinkerization). The wet process uses rotary kilns exclusively. The dry process can also employ simple rotary kilns. Thermal efficiency can be improved, however, through the use of one or more cyclone-type preheater vessels that are arranged vertically, in series, ahead of the rotary kiln in the material flow path. It can be further improved by diverting up to 60% of the thermal energy (i.e., fuel) required by the pyroprocessing system to a special calciner vessel located between the preheater vessels and the rotary kiln.

The rotary kiln is the heart of the portland cement process since the several and complex chemical reactions necessary to produce portland cement minerals take place there. The portland cement kiln is a slightly inclined, slowly rotating steel tube that is lined with appropriate refractory materials. The rotation of the kiln causes the solid materials to be slowly transported downhill from the feed end. Fuel is supplied at the lower or discharge end of the kiln. Many fuels can be used

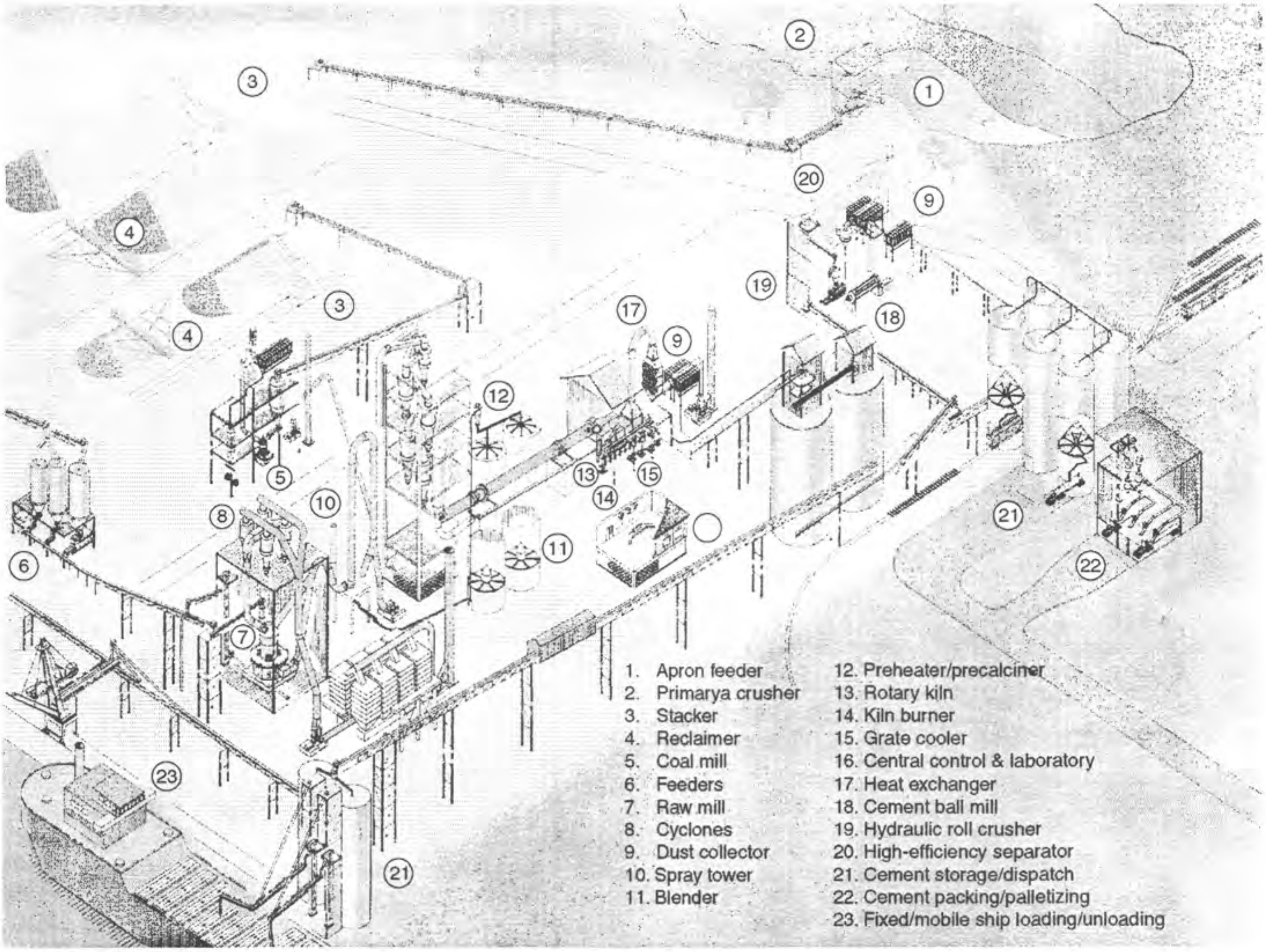

**Figure 2.** Cement Plant Layout.

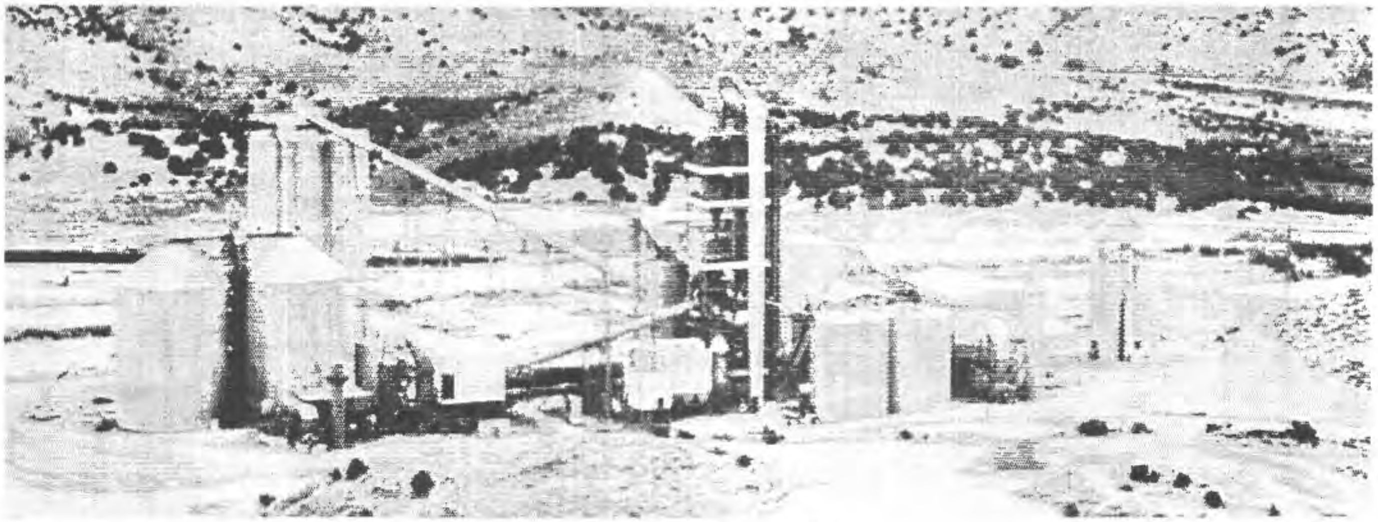

**Figure 3.** Modern Cement Plant.

in the kiln, but coal has predominated in the United States since the mid-1970s. The choice of fuel is based on economics and availability. The hot, gaseous combustion products move countercurrent to the material flow, thereby transferring heat to the solids in the kiln load.

Flame temperatures in excess of 3400°F result in the material temperatures of 2700–2800°F that are required to produce the hydraulic calcium and aluminum silicates. In effect, the cement pyroprocess converts natural sedimentary rocks into synthetic igneous rocks.

The product of the rotary kiln is known as clinker. Heat from just produced clinker is recuperated in a clinker cooling device and returned to the pyroprocess by heating combustion air for the kiln and/or calciner.

The cooled clinker is mixed with a form of calcium sulfate, usually gypsum, and ground in ball or tube mills in the finish mill department to produce portland cement. Masonry cement is similarly produced from portland cement clinker, gypsum, and one or more calcareous materials.

Portland cements are shipped from the packhouse or shipping department in bulk or in paper bags by truck, rail, barge, or ship. Masonry cements are shipped primarily in paper bags.

Except for the quarry and rock crushing operations, and indirect-fired coal mill systems, the New Source Performance Standards (NSPS) that apply to a new or modified portland cement plant constructed after August 17, 1971, are contained in 40 CFR 60, Subpart F, *Standards of Performance for Portland Cement Plants.*

Emission factors for portland cement plants are contained in Section 11.6 of the United States Environmental Protection Agency (EPA) publication, *Compilation of Air Pollutant Emission Factors*, AP-42, Fifth Edition, January 1995. Tables of these emission factors occupy several pages in AP-42 and have not been included here.

An explanation of the operation of the common dust collection devices used in the cement industry, such as multiclones, fabric filters, and electrostatic precipitators (ESPs), is beyond the scope of this chapter but can be found elsewhere in this manual.

## ACQUISITION OF RAW MATERIALS

### Process Description

The initial step in the manufacture of portland cement is the acquisition of raw materials. The industry is considered an extractive industry since nearly all the required raw materials are obtained from the earth's crust by mining or quarrying. Most cement plants are located near a source of $CaCO_3$, which is most often limestone. Since about one-third of the weight of the limestone is lost as $CO_2$ during pyroprocessing, process economics dictate that this lost weight be transported as short a distance as possible. Those plants that are not immediately associated with a limestone quarry often have a source of limestone or other form of $CaCO_3$ (e.g., aragonite) that is available by less expensive water transportation. However, there are a few exceptions to these generalizations on plant location.

Calcium is the metallic element of highest concentration in portland cement. The calcareous raw materials can include limestone, chalk, marl, aragonite, and an impure limestone known in the industry as natural cement rock. Limestone, chalk, and cement rock are most often extracted from open-face quarries, but underground mining can be employed. Dredging and underwater mining techniques are used to develop deposits of calcareous raw materials in the ocean or below the water table. Gypsum and/or natural anhydrite (i.e., forms of calcium sulfate) from quarries or mines are calcium-bearing constituents of portland cement that are introduced as part of the final stage of its manufacture, finish grinding. It is rare for a cement plant to have a captive source of gypsum or anhydrite and these materials are usually purchased.

Silicon, aluminum, and iron are the next most prevalent metallic elements in normal portland cement and are listed in descending order of concentration. These metals are found in various siliceous, argillaceous, and ferriferous ores and minerals, such as sand, shale, clay, and iron ore. Although usually extracted in open-face quarries or pits, these raw materials can be dredged or excavated from underwater deposits. They can be obtained from captive sources adjacent to or away from the portland cement plant; however, it is often necessary or economical for the cement manufacturer to purchase them from outside sources.

The wastes and by-products of other industries are successfully employed as portland cement raw materials. Such materials include, but are not limited to, power plant fly ash, steel mill scale, and metal smelting slags.

The cement manufacturing process and the performance of portland cement are sometimes affected by trace elements that are found in virgin raw materials or wastes. Care must be exercised in selecting these raw materials to assure that trace elements will not be present in high enough concentrations to cause problems in the plant or with the product.

## AIR EMISSIONS CHARACTERIZATION

Quarries at cement plants are similar to other stone quarries. The necessary operations include rock drilling, blasting, excavation, loading, hauling, crushing, screening, materials handling, stockpiling, and storing. There are many different operating methods, types of equipment, and equipment brands that are used to accomplish these tasks. Particulate matter is the primary air pollutant associated with quarry operations. In some locations (e.g., an underground mine), exhaust emissions from mobile equipment may be of concern. There are usually no atmospheric air pollution problems at underground mines or underwater operations.

The NSPS that apply to quarry and crushing operations at portland cement plants are contained in 40 CFR 60, Subpart 000, *Standards of Performance for Nonmetallic Mineral Processing*. These standards are applicable to those affected facilities that commenced construction, reconstruction, or modification after August 31, 1983.

Raw materials can also be the source of some environmentally undesirable emissions from the kiln stack found later in the process. If the raw materials contain naturally occurring hydrocarbons, such as petroleum or kerogens, these materials can evaporate or pyrolize in the relatively cooler portions of the pyroprocessing system and appear at the stack exit as a visible "blue haze" or as invisible organic constituents. Sulfur and chlorine from the raw materials can participate in reactions with the small amount of ammonia sometimes found in cement kiln emissions to form a "detached plume" of ammonium sulfate or ammonium chloride. Nitrogenous constituents of the raw materials can possibly contribute to emissions of nitrogen oxides ($NO_x$) emissions that are unrelated to combustion. Sulfides in raw materials contribute to sulfur dioxide ($SO_2$) emissions under the process conditions found in all preheater or precalciner kilns.

## AIR POLLUTION CONTROL MEASURES

Control measures for particulate emissions in quarries include water sprays with and without surfactants, foams, chemical dust suppressants, wind screens, equipment enclosures, paving, mechanical collectors and fabric filters on operating equipment, and material storage buildings, enclosures, bins, and silos with and without exhaust venting to fabric filters. Collected dust is returned to the process.

Typical fabric filters found in the quarry are pulse jet types in newer plants and reverse air or shaker types in the older plants (see Table 1).

Purchased raw materials, including coal or petroleum coke used for fuel, can also generate particulate emissions as a result of vehicle loading and unloading, material handling, stockpiling, and haulage. The particulate emission control measures for purchased materials are the same as those listed for quarries.

## RAW MILLING

### Process Description

The second step in the manufacture of portland cement is the preparation of the raw materials for pyroprocessing. This operation in the raw mill department combines the blending of appropriate raw materials for proper chemical composition with particle-size reduction through grinding.

Grinding is required to achieve optimum fuel efficiency in the cement kiln and to develop maximum strength and durability potential in portland cement concrete. Typically, the raw material in the kiln feed is ground to about 85% passing a 200-mesh (74-μm) sieve or 90% passing a 170-mesh (88-μm) sieve. Usually less than 1% of the material is retained on a 50-mesh (297-μm) sieve. The actual fineness that is required depends on the reactivity of the raw material components. Excessive grinding of raw materials wastes energy and reduces the productive capacity of the raw mill. Raw milling processes are either wet or dry, depending on the type of pyroprocessing system(s) at the plant.

When raw materials are dried before grinding or when the physical properties of the moist materials permit handling, the raw materials are usually proportioned with weigh feeder systems located in the process flow ahead of a mill feed bin or the raw mill itself. If required and justified by process economics, raw materials can also be proportioned and blended in large (e.g., 1000-ft-long) linear or circular stacker–reclaimer systems that are frequently located in closed buildings.

Cement raw materials are received in the raw mill department with a moisture content varying from 2% to 35%. In the dry process, this moisture is usually reduced to less than 1% before or during grinding. Drying prior to grinding is accomplished in impact dryers, drum dryers, paddle-equipped rapid dryers, air separators, or autogenous mills. Drying can also be carried out during grinding of the raw mix in ball-and-tube mills or roller mills. Thermal energy for drying can be supplied by separate, direct-fired coal, oil, or gas burners that heat the airstream that passes through the drying apparatus or mill. The most efficient and popular source of heat for drying is the hot exit gases from the pyroprocessing system. These gases can come from the kiln, the clinker cooler, the alkali bypass system, or a combination of these sources. Unless the hot gases are supplied solely from the clinker cooler, the gases passing through dryers and raw mills will contain products of combustion, as well as solid particles. The selection of the drying method depends on the physical properties of the raw materials, the type of pyroprocessing system in the plant, the availability and cost of energy, and the preferences of owners, managers, and vendors.

Ball-and-tube mills (i.e., long ball mills) are rotating, horizontal steel tubes that contain steel balls and are used to provide comminution or grinding of the raw materials. Air separators are frequently used in conjunction with these mills in the dry process to separate materials of adequate fineness from the coarse particles that must be returned to the grinding mill for additional work (i.e., closed-circuit grinding). The design and operation of these mills and air separators are discussed in the following description of finish milling. The hot gases required for simultaneous drying and grinding in a ball mill system can enter the feed end of the mill and flow concurrently with the raw materials. Otherwise, the unground raw materials and the hot gases are introduced simultaneously into the air separator. Some operators feel that this latter procedure provides for more efficient drying, easier operation of the mill circuit, and early removal from the mill system of those materials that are already sufficiently ground. The separator does, however, experience additional wear.

**Table 1. Fabric Filters in Quarries**

| | Pulse Jet | | | Reverse Air/Shaker |
|---|---|---|---|---|
| Acfm | 5,000–25,000 | 5,000–25,000 | 5,000–25,000 | 5,000–25,000 |
| Filter design | Tubular bag | Pleated | PTFE membrane on tubular bag | Tubular bag |
| Filter type | Polyester | Spun-bonded polyester | Felt with PTFE membrane | Polyester |
| Temp.(°F) | <275 | ≤265 | ≤275 | <275 |
| A/C ratio[a] | ≤5:1 | ≤3.5:1 | ≤5.5:1 | ≤2.5:1 |
| Inlet loading (gr/acf) | 5–40 | 5–40 | 5–40 | 5–40 |
| Outlet emission (gr/acf) | <0.02 | <0.01 | <0.005 | 0.02 |

[a] Air-to-cloth ratio (acfm/$ft^2$).

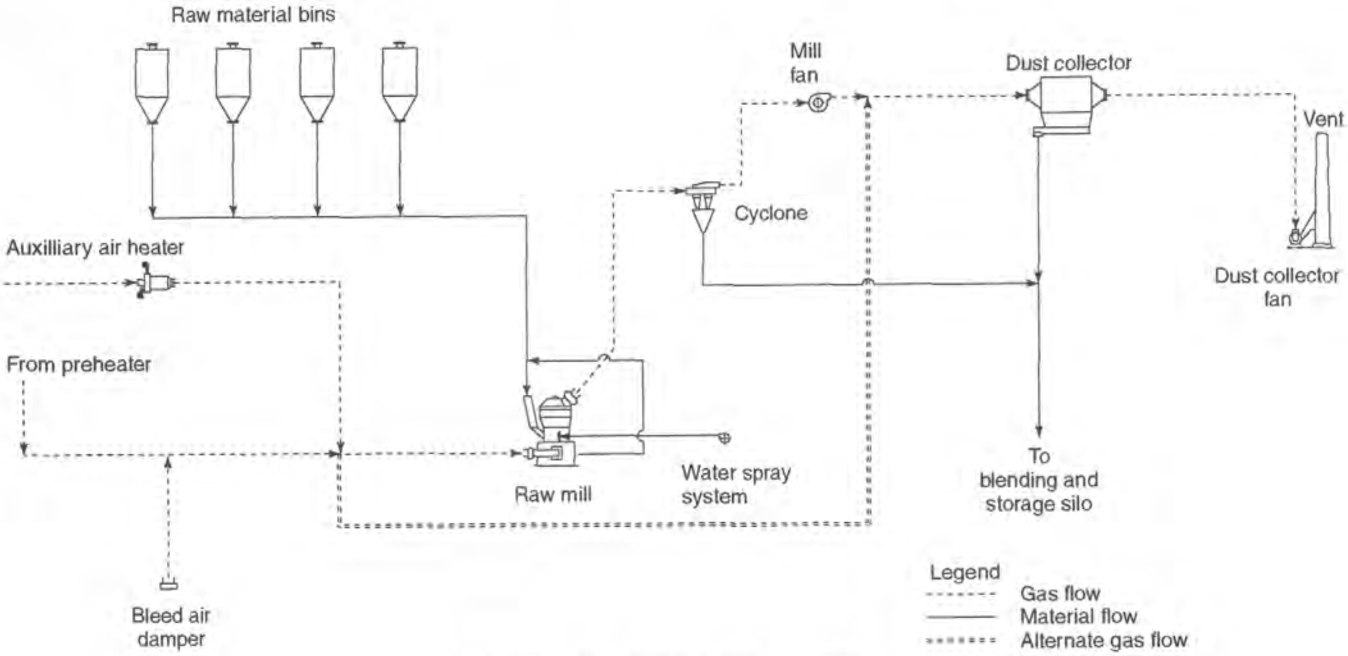

**Figure 4.** Raw Mill Schematic Diagram.

Vertical roller mills are very popular in new, dry-process portland cement plants because of their relative simplicity and high efficiency. The principle of operation of these mills is similar to that of a mortar and pestle. In this case, the pestle (roll) is stationary and the mortar (table) rotates. Raw materials are dropped on the rotating table to be crushed and ground between the rolls and the table. Hot gases enter the mill through an annular duct at table height. As ground material is forced off the table into the hot gas stream, it is entrained in the gases, dried, and transported upward to internal separators from which coarse material is returned to the mill by gravity. Product is captured in the air pollution control device (e.g., fabric filter). Figure 4 is a process diagram of a typical vertical roller mill raw milling circuit. Figure 5 shows an installed roller mill.

Materials are transported to, within, and away from dry raw milling systems by a variety of mechanisms, including screw conveyors, belt conveyors, drag conveyors, bucket elevators, air slide conveyors, and pneumatic conveying systems.

The dry raw mix is pneumatically blended and stored in specially constructed silos until it is fed to the pyroprocessing system.

In the wet process, water is added to the raw mill during the grinding of the raw materials in ball or tube mills, thereby producing a pumpable slip or slurry of approximately 65% solids. The slurry is agitated, blended, and stored in various kinds and sizes of cylindrical tanks or slurry basins until it is fed to the pyroprocessing system. Until recently, the advantage of the wet process was that the chemical composition of the kiln feed could be controlled more closely since slurries blend more easily than powders. Modern equipment can now blend raw meal powders satisfactorily.

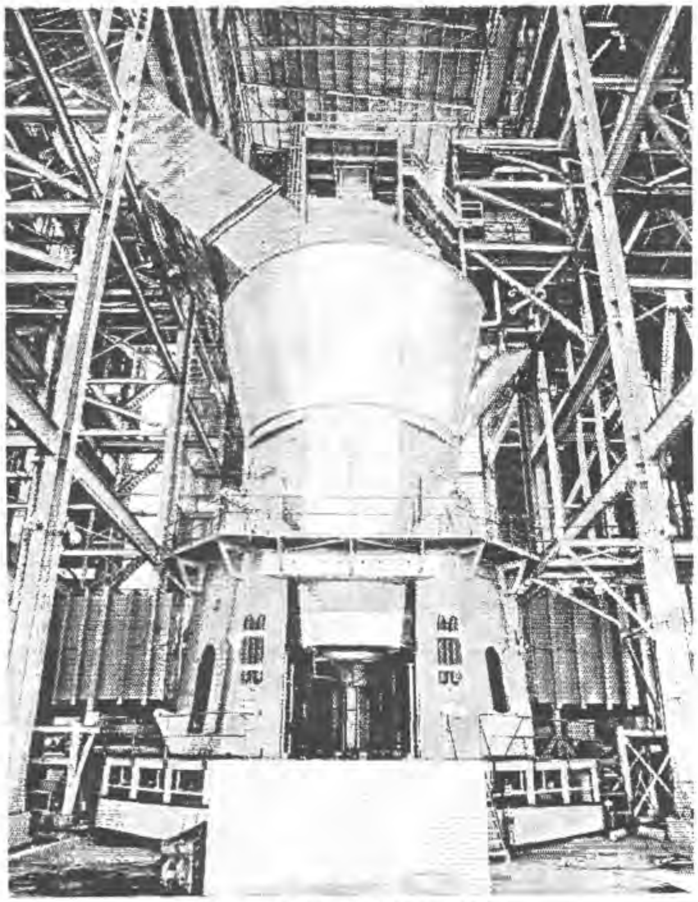

**Figure 5.** Vertical Roller Mill.

## AIR EMISSIONS CHARACTERIZATION

The raw material feeders, stackers, blenders, and reclaimers can produce fugitive dust emissions. Transfer points on belt conveyor systems and bucket elevators that serve to transport raw materials from storage to the raw mill department can also generate fugitive dust emissions.

The dry raw mills and the auxiliary equipment are all designed to run under negative pressure to suppress particulate emissions. Nevertheless, poorly designed or maintained seals and closures throughout the system can result in fugitive dust emissions. If these systems experience positive pressure through a fan failure or other cause, short-term particulate emissions can be expected until the system can be shut down.

During colder weather, the vents from dryers, raw mills, and air separators may exhibit a steam plume that is sometimes confused with particulate emissions. The condensate will dissipate within a few feet of the emission point. Fabric filters in the vent circuits for dryers, raw mills, and air separators must be insulated to prevent internal moisture condensation and the resultant blinding of bags.

There are no particulate emissions from the wet grinding process, except for the materials-handling systems ahead of the mills.

## AIR POLLUTION CONTROL MEASURES

Dust collecting devices in the raw mill and raw mix storage areas include mechanical cyclones, fabric filters, and, rarely, electrostatic precipitators (ESPs). When employed, mechanical collectors are used in series with one of the other, more efficient dust collection devices. The collected dust is returned to the mill system or raw mix stream.

Typical fabric filters found in the raw mill area are pulse-jet types in the newer or upgraded plants and reverse-air or shaker types in the older plants. Cartridge-type filters can be found on materials-handling equipment (see Table 2). Vertical mills are most often closely coupled to the pyroprocessing system. The air pollution control measures for these mills will be found in the following section on pyroprocessing.

## PYROPROCESSING

### Process Description

The third step in the manufacture of portland cement is the pyroprocessing of the raw mix into portland cement clinker. Clinkers are gray-colored, glass-hard, spherical-shaped nodules that generally range from 1/8 to 2 in. in diameter. The clinkers are predominantly composed of the cement minerals, tricalcium silicate, dicalcium silicate, calcium aluminate, and tetracalcium aluminoferrite, which result from chemical reactions between the cement raw materials that are completed at the temperature of incipient fusion. The chemical reactions and physical changes that describe the transformation are very complex. A simplified version of the major sequential events is as follows:

- Evaporation of free water
- Evolution of combined water in the argillaceous components
- Calcination of the $CaCO_3$ to calcium oxide (CaO)
- Reaction of CaO with silica to form dicalcium silicate
- Reaction of CaO with the aluminum and iron-bearing constituents to form the liquid phase (i.e., aluminate and aluminoferrite)
- Formation of the clinker nodules
- Evaporation of volatile constituents (e.g., sodium, potassium, chlorides, and sulfates)
- Reaction of excess CaO with dicalcium silicate to form tricalcium silicate

The pyroprocessing system is generally described as containing three steps or zones: (1) drying or preheating, (2) calcining, and (3) burning or sintering. The pyroprocessing is accomplished in the burning or kiln department. The word *burning* is jargon that is used in the cement industry to describe the intense heat in this zone of the kilns. None of the constituents of the cement raw mix actually combusts during pyroprocessing.

The raw mix is fed to the pyroprocessing system as a slurry in the wet process, as a powder in the dry process. A rotary kiln is the common element in all pyroprocessing systems, and it will always contain the burning zone and all or part of the calcining zone. All the pyroprocessing steps occur in the rotary kiln in wet-process and long, dry-process (i.e., no preheater) systems. The application of chemical engineering principles to cement pyroprocessing has resulted in equipment additions to the rotary kiln system that can accomplish preheating and most of the calcining more quickly and efficiently outside the kiln. Rotary kilns are rotating, cylindrical steel tubes with length-to-diameter ratios in the approximate range of 15:1 to 35:1. The size of the kiln and its relative proportions are determined by the type and capacity of the pyroprocessing system. Wet-process kilns of over 700 ft in length and 23 ft in diameter are in operation. However, many wet and all dry-process kilns in the United States are smaller. Dry-process kilns that are equipped with preheaters are shorter yet. The kiln rotates about the longitudinal axis, which is slightly inclined to the horizontal, at a speed of from 1 to 3.5 rpm.

**Table 2. Fabric Filters for Raw Mill Systems**

| | Pulse Jet | | | Reverse Air/Shaker |
|---|---|---|---|---|
| Acfm | 10,000–50,000 | 10,000–50,000 | 10,000–50,000 | 10,000–50,000 |
| Filter design | Tubular bag | Pleated | PTFE membrane on tubular bag | Tubular bag |
| Filter type | Polyester | Spun-bonded polyester | Felt with PTFE membrane | Polyester |
| Temp.(°F) | <275 | ≤265 | ≤275 | <275 |
| A/C ratio[a] | ≤5.0:1 | ≤2.5:1 | ≤5.5:1 | ≤2.5:1 |
| Inlet loading (gr/acf) | 5–20 | 5–20 | 5–20 | 5–20 |
| Outlet emission (gr/acf) | <0.02 | <0.01 | <0.005 | 0.02 |

[a] Air-to-cloth ratio (acfm/ft$^2$).

Refractory material lines the kiln to protect the steel shell from the intense heat and to retain heat within the kiln. The inclination and rotation of the tube result in the transport of solid materials from the upper or feed end to the lower or discharge end. The solids (i.e., load) occupy no more than 15–20% of the internal volume of the rotary kiln inside the refractory. There will be hundreds of tons of material within the kiln at any particular time. Material transit time is measured in hours for long kilns and in fractions of hours for preheater or calciner kilns. Heat energy is supplied at the discharge end of the kiln by the combustion of a variety of fuels. The flow of hot, gaseous combustion products is, therefore, countercurrent to the material flow. Heat is transferred from the flame and hot gases to the solid materials to provide the driving force for the required chemical reactions. The solid material is heated to about 2700°F by flame temperatures in excess of 3400°F.

Wet-process and long, dry-process pyroprocessing systems consist solely of the simple rotary kiln. Heavy chains are suspended in the drying or preheat zone at the feed end of the kiln to improve heat transfer from the hot gases to the solid materials. These chains are attached to the inside of the kiln shell in various patterns. As the kiln rotates, the chains are raised and exposed to the hot gases. Further kiln rotation causes the hot chains to fall into the cooler materials at the bottom of the kiln, thereby transferring the heat to the load.

Dry-process pyroprocessing systems have been improved in thermal efficiency and productive capacity through the addition of one or more cyclone-type preheater vessels in the gas stream after the rotary kiln. The vessels are arranged vertically, in series, and are supported by a structure known as the preheater tower. Hot exhaust gases from the rotary kiln pass countercurrent through the downward-moving raw materials in the preheater vessels. Compared with the simple rotary kiln, the heat transfer rate is significantly increased, the degree of heat utilization is more complete, and the process time is markedly reduced owing to the intimate contact of the solid particles with the hot gases. The required length and material retention time of the rotary kiln is thereby reduced.

The hot gases from the preheater tower are often used as a source of heat for the drying of raw materials in the raw mill. The mechanical collectors, fabric filters, and/or ESPs that follow the raw mill are production machines capturing valuable product as well as pollution control devices.

Additional thermal efficiencies and productivity gains have been achieved by diverting some fuel to a calciner vessel at the base of the preheater tower. At least 40% of the thermal energy is required in the rotary kiln. The amount of fuel that is introduced to the calciner is determined by the availability and source of the oxygen for combustion in the calciner. If available and allowed by environmental regulations, calciner systems can use lower-quality fuels (e.g., less volatile matter) and thereby further improve process economics.

In preheater and calciner kiln systems, it is possible efficiently to remove undesirable volatile constituents through a bypass system located between the feed end of the rotary kiln and the preheater tower. Otherwise, the volatile constituents would condense somewhere in the preheater tower and subsequently recirculate to the kiln. Buildups of these condensed materials can also restrict process flows by blocking gas and material passages. In a bypass system, a portion of the kiln exit gas stream is withdrawn and quickly cooled by air or water to condense the volatile constituents to fine particles. The solid particles are removed from the gas stream by fabric filters or ESPs.

Figure 6 is a flow diagram of a four-stage preheater with a calciner pyroprocessing system that is equipped with an alkali bypass and a reciprocating grate clinker cooler. Figure 7 shows

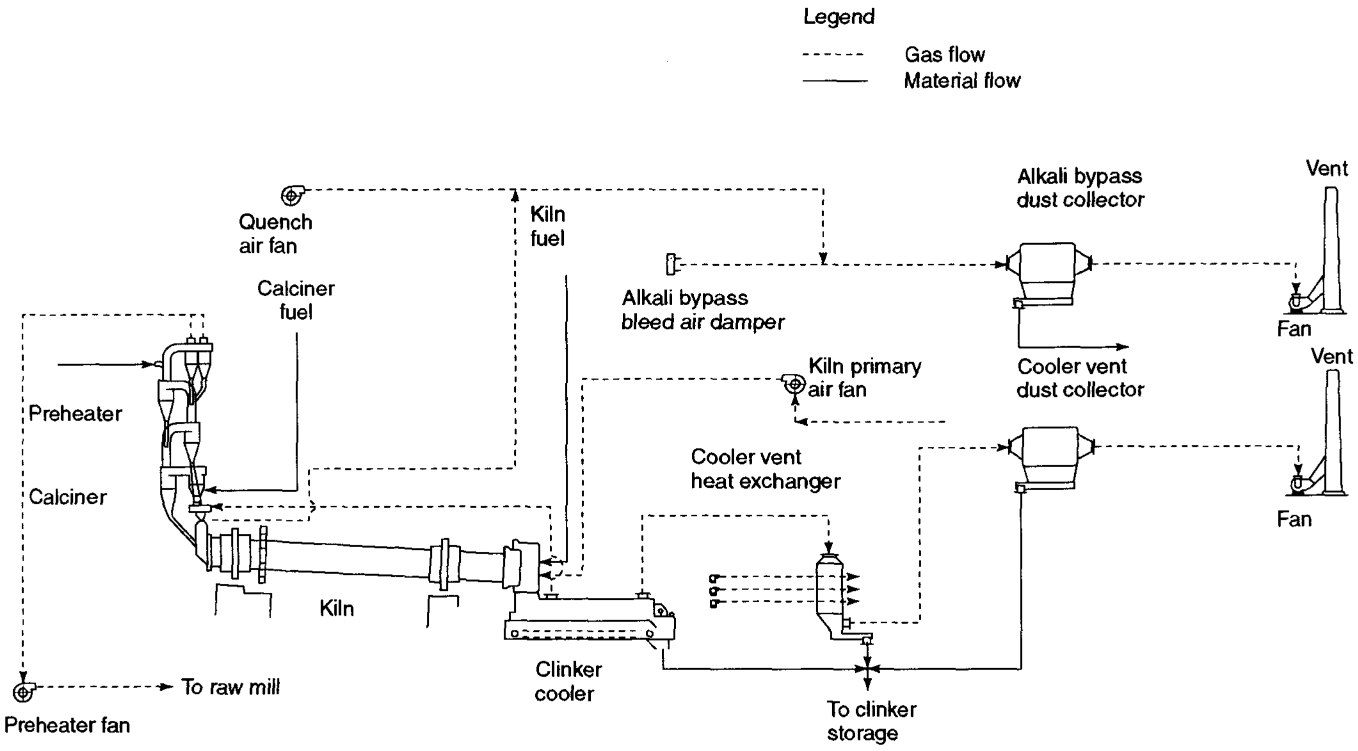

**Figure 6.** Pyroprocessing System Schematic Diagram.

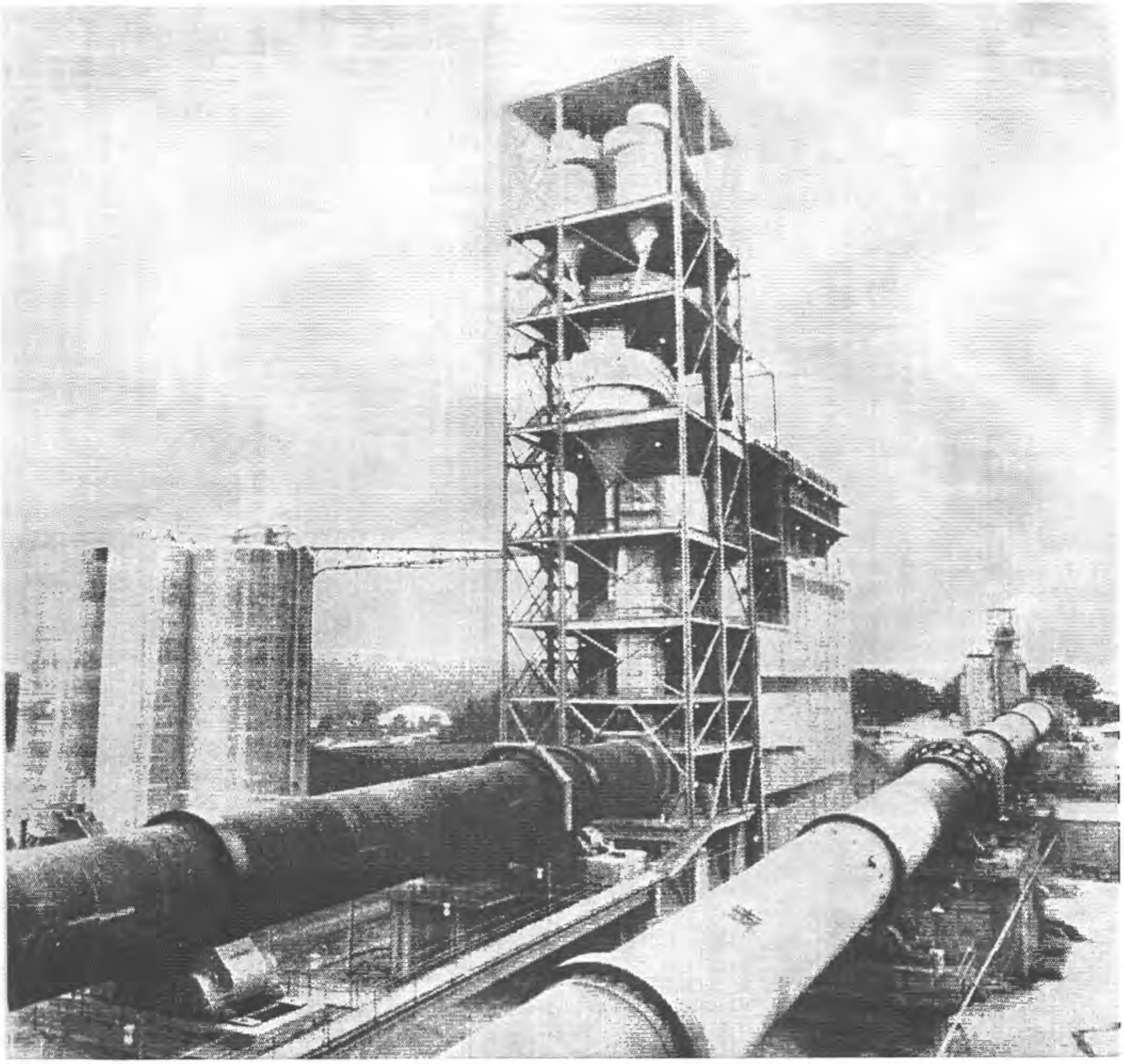

**Figure 7.** Preheater and Rotary Kilns.

a four-stage preheater kiln system next to a traditional rotary kiln.

Solid fossil fuels (i.e., coal and petroleum coke) are ground to a fine powder [e.g., 80% passing a 200-mesh (74-μm) sieve] before being blown into the rotary kiln or calciner for combustion. Two classes of coal preparation systems are employed, direct and indirect firing. Direct-firing systems were exclusively found in older plants, but many of these systems have been converted to or replaced by indirect firing. New plants are equipped with indirect firing systems. Indirect firing systems are covered by NSPS contained in 40 CFR 60, Subpart Y, *Standards of Performance for Coal Preparation Plants*. Because direct-fired systems do not vent directly to the atmosphere, these standards do not apply to them.

Direct-fired coal/coke systems obtain hot air for drying and material transport from the clinker cooler or kiln hood. Solid fuel is fed to the coal mill, dried, ground, and transported directly to the burning zone of the rotary kiln without storage. The relatively large quanity of air required for drying results in more primary air in the flame than is desirable. Excess primary air contributes to inefficient combustion and unnecessary $NO_x$ formation. Direct-fired systems are unsuitable for firing coal in calciners or in a riser duct for $NO_x$ control.

Most often, indirect-fired coal/coke systems obtain the hot air for drying and material transport from the pyroprocessing system exhaust. Hot gases from the clinker coller can be used if proper safety precautions are taken. The ground coal is collected in a fabric filter and temporarily stored in feed bins prior to introduction into the burning zone of the rotary kiln, the calciner, or the riser duct. Relatively small quantities of ambient air are required to transport the independently metered quantities of solid fuel from the storage bin to the selected firing point. Indirect firing is a prerequisite for the installation of low-$NO_x$ burners in the rotary kiln. Storing and handling powdered coal has the potential for fires and explosions; therefore, safety systems are installed to minimize the chance of catastrophic events.

### Air Emissions Characterization

In simple rotary kiln systems, some finely divided particles of raw mix, calcined kiln feed, clinker dust, and volatile constituents (e.g., potassium sulfate) are entrained in the exiting gas stream. These particles are almost entirely removed from the gas stream before the combustion products are vented to the atmosphere. Affected pyroprocessing systems always meet or exceed the NSPS for particulate emissions from portland cement plants. Even those plants built prior to 1971 that are not subject to NSPS usually meet these standards for particulate emissions.

The powder that is collected from the kiln exhaust gases is known as cement kiln dust (CKD). Most plants return all or a portion of the CKD to the process; others completely remove it from the process. The chemical composition and physical state of the CKD depend on the type of pyroprocessing system, the chemical composition of the raw materials and fuel, and the state of the process at any given time. The composition of the relatively coarse CKD that is caught in the first field of an ESP is similar in chemical and physical characteristics to the raw mix, and in the last field it is very similar to that of the finer particulate emissions from the kiln stack. The same generalization cannot be made about CKD caught in a fabric filter, since there is almost no segregation of particles in a fabric filter. Specifications for portland cement often contain limitations on the quantity of sodium and potassium. Since the volatile oxides and salts of these metals tend to migrate or partition to the CKD, a portion or all of the CKD is sometimes removed from the pyroprocessing system to meet product quality standards. Bypass CKD is rich in sodium and potassium and is not returned to the process. The dust emanating from a preheater tower has the same general chemical and physical composition as the kiln feed and is returned to the process. The CKD that is removed from the system can be used for a variety of beneficial purposes (e.g., waste stabilization) or is managed at the cement plant in a monofill. The handling, storage, and deposition of CKD can result in fugitive dust emissions.

The cleaned bypass gases may be used in the raw mill, vented through a separate stack, or combined with kiln gases in the main kiln stack. The preheater gases may be vented to the atmosphere after particulate removal or used in the raw mill with no treatment other than temperature control. If the plant was built or modified after August 17, 1971, the preheater and bypass exit gases must meet the NSPS opacity limit of 20% and a mass emission limit of 0.15 kg/mg of particulate emissions per metric ton (0.30 lb/ton) of dry kiln feed on a combined basis from all emission points, regardless of the treatment or use of combustion products and tempering air from the pyroprocessing system. The principal gaseous emissions from the pyroprocessing system in a typical descending order by volume are nitrogen, $CO_2$, water, oxygen, $NO_x$, $SO_2$, CO, and hydrocarbons. The volumetric composition range of these constituents is from about 73% to less than 10 ppm. $CO_2$ and the last four listed gases are the primary constituents of environmental concern.

Emission rates of $SO_2$ and $NO_x$ display a wide range of values throughout the industry. It is impossible to characterize the industry for gaseous emissions of $SO_2$ and $NO_x$ with a single number or narrow numerical range. Each individual pyroprocessing system has its own emission characteristics, and the $SO_2$ and $NO_x$ emissions from proposed or untested pyroprocessing systems are sometimes difficult to predict accurately. Extensive continuous monitoring of several cement plants has shown that $SO_2$ and $NO_x$ emissions from a single source will normally vary over a rather large range (e.g., an order of magnitude). Short-term tests, such as EPA Methods 6 and 7, can lead to very erroneous conclusions regarding $SO_2$ and $NO_x$ emissions, since these methods represent nearly instantaneous process conditions.

Sulfur input to a pyroprocessing system is only from feed and fuel. The relative amounts of sulfur in the feed and fuel, the system design, the chemical form of the input sulfur, and the process conditions, such as the presence of an oxidizing or reducing atmosphere in the kiln, are the variables that determine the quantity of $SO_2$ emissions at any given time. Oxides of nitrogen result primarily from the combustion of fuel, although nitrogenous constituents in the raw mix may make a contribution to $NO_x$ emissions. The two primary sources of $NO_x$ from fuel combustion are known as fuel and thermal $NO_x$. Nitric oxide (NO) predominates among the oxides of nitrogen that are emitted from cement pyroprocessing systems.

The current NSPS for cement plants recognize the uncertainty about $SO_2$ and $NO_x$ emission rates from cement kilns and the absence of widely used control technology through the absence of any emission standards for these pollutants. It is often necessary, however, to include air pollution permit limitations on $SO_2$ and $NO_x$ emissions from cement plants to meet prevention of significant deterioration (PSD) regulatory requirements and/or ambient air quality standards. Attempts to control emissions of $SO_2$ and $NO_x$ from cement plants are becoming more prevalent and are meeting with success.

Indirect-firing coal systems can divert approximately 10% of the pyroprocess exit gases to the coal mill to dry the solid fossil fuel. These gases contain the products of combustion and calcination. If the coal mill is vented through a stack with a relatively low elevation, the constituents in these gases may dominate the ambient dispersion modeling for the plant. It may be necessary to recombine the coal mill vent gases with the balance of the kiln gases in the main stack to better disperse the coal mill vent gases. If the gases are combined, the more stringent NSPS standard for coal preparation plants will apply to the main stack. Fabric filters on coal mill applications generally have electrically grounded filter bags to eliminate static charges on the filter medium. If electrical sparks occur, a coal-dust explosion or fire could result. Explosion venting is normally included the fabric filter design to reduce the damage to the filter bags and/or the fabric filter enclosure if an explosion were to occur. Explosion venting also provides a pressure relief so that fire does not damage in-line equipment. The fabric filters used in coal mill applications are made from common filter media such as polyester, acrylic, and spun-bonded polyester. PTFE membrane is sometimes added to the filter medium to reduce the amount of coal dust retained on the filter and to lower the pressure drop across the dust collector. Air pollution control equipment on the indirect coal systems is pulse-jet fabric filters (see Table 3).

**Table 3. Fabric Filters for Indirect-Fired Coal Systems**

| | Pulse Jet | | |
|---|---|---|---|
| Acfm | 10,000–50,000 | 10,000–50,000 | 10,000–50,000 |
| Filter design | Tubular bag | Pleated[a] | PTFE membrane on tubular bag |
| Filter type | Polyester | Spun-bonded polyester | Felt with PTFE membrane |
| Temp.(°F) | ≤275 | ≤265 | ≤275 |
| A/C ratio[b] | ≤4:1 | ≤2.0:1 | ≤4:1 |
| Inlet loading (gr/acf) | 10–55 | 10–55 | 10–55 |
| Outlet emission (gr/acf) | <0.02 | ≤0.01 | ≤0.005 |

[a] Not recommended when blending petroleum coke.

[b] Air-to-cloth ratio (acfm/ft$^2$).

## AIR POLLUTION CONTROL MEASURES

Air pollution control equipment on the kiln system includes reverse air fabric filters, pulse-jet fabric filters, and ESPs. Acoustic horns are sometimes used in both devices to assist in cleaning (see Table 4). Cement kiln systems have highly alkaline internal environments that can absorb up to 95% of potential $SO_2$ emissions. Exceptions to the generalization are found in systems that have sulfide sulfur (pyrites) in the kiln feed. Without unique design considerations or changes in raw materials, the overall sulfur absorption rate may be as low as 70%. Historically, the cement kiln system itself has been determined to be best available control technology (BACT) for $SO_2$ emissions. In fabric filters, there must be an absorbing reagent (e.g., CaO) in the filter cake for $SO_2$ capture to occur. Without the presence of water, which is undesirable in the operation of a fabric filter, $CaCO_3$ is not an $SO_2$ absorbing reagent. It has been observed that as much as 50% of the $SO_2$ can be removed from the pyroprocessing system exhaust gases when this gas stream is used in an in-line raw mill for heat recovery and drying. In this case, moisture and calcium carbonate are simultaneously present for sufficient time to accomplish the chemical reaction with $SO_2$. Vendors of cement pyroprocessing systems are developing methods to recirculate calcined raw mix or CKD to the process to provide calcium oxide as a reagent for additional internal scrubbing of $SO_2$. When ambient air quality standards have been threatened, a small number of proposed cement kilns are installing tail pipe wet scrubbers that use calcium carbonate as the reagent for $SO_2$ removal.

Energy-efficient pyroprocessing systems have the potential to emit less $SO_2$ than inefficient systems because of the lower sulfur input resulting from reduced fuel consumption. In addition, preheater and calciner kilns have the capacity to absorb relatively large quantities of fuel-derived $SO_2$. Similarly, raw materials with the lowest content of sulfide sulfur can result in the lowest $SO_2$ emissions. Selective quarrying or a change in raw materials can lower the input of sulfur to the pyroprocessing system. As noted previously, pyroprocessing systems with in-line raw mills are able to absorb up to half of the potential $SO_2$ emissions when the mill is in operation.

Several mechanisms for the control of $NO_x$ emissions from cement kilns are in existence. They meet with varying degrees of success. Stable kiln operation, such as is often found in a precalciner system, has been shown to minimize cumulative, long-term $NO_x$ emissions. However, short-term spikes of $NO_x$ emissions during process upsets are unavoidable, since a higher than normal input of thermal energy from the combustion source is required to restore the process to equilibrium. Several equipment vendors sell burner configurations for the rotary kiln that are alleged to reduce $NO_x$ emissions. A form of staged combustion can be used on preheater or precalciner kilns to reduce $NO_x$ emissions. Fuel is burned under reducing conditions in the riser duct from the rotary kiln to the preheater or precalciner to generate CO. This CO chemically reduces the $NO_x$ generated in the kiln to elemental nitrogen. The oxygen-deficient gases thereby generated can be supplied to the calciner to further reduce $NO_x$ generation in that low-temperature combustion source. Pyroprocessing system vendors offer other, similar methods to achieve $NO_x$ reduction through combustion with oxygen-deficient gases or reaction of $NO_x$ with CO. It is possible to inject ammonia or urea into a preheater tower at a point where

**Table 4. Kiln System Dust Collectors**

| | Reverse Air | | Pulse Jet | Precipitator |
|---|---|---|---|---|
| Acfm | 50,000–300,000 | 50,000–300,000 | 50,000–300,000 | 50,000–300,000 |
| Filter design | Tubular bag | Tubular bag | Tubular bag | N/A |
| Filter type | Fiberglass | Fiberglass with PTFE membrane | Fiberglass with PTFE membrane | N/A |
| Temp.(°F) | 350–500 | 350–500 | 350–650 | 350–650 |
| A/C ratio[a] | 1.5:1 net | 2.0:1 | ≤3.5:1 net | SCA: 350–500[b] |
| Inlet loading (gr/acf) | 4–18 | 4–18 | 4–18 | 4–18 |
| Outlet emission (gr/acf) | 0.02 | <0.005 | 0.005 | 0.02 |

[a] Air-to-cloth ratio (acfm/ft$^2$).

[b] Specific collecting area (ft$^2$/1000 acfm).

consists solely of cement minerals and is returned to the process.

The quantity of air used for cooling is about 1–3 pounds per pound of clinker, depending on the efficiency of cooling and the desired temperature of the clinker and vent gas. If some of the gases are used for the drying of coal or for other purposes, then the volume of gas to be cleaned at the cooler vent may be reduced by 10–100%.

The dust content of the cooler exhaust gases is affected by the granular distribution of the clinker, the degree of burning of the clinker, the bulk density of the clinker (i.e., liter weight), and the flow rate of the cooling air. Frequently, a clinker breaker (e.g., hammer mill) is located at the discharge of the cooler and may increase the dust burden.

If applicable, NSPS specify a mass emission limit on the cooler vent stack of 0.05 kg/mg of particulates per metric ton (0.10 lb/ton) of dry kiln feed. An opacity limit of 10% also applies to the cooler stack. If the cooler gases are used for drying in the raw mill, the more stringent mass emission and opacity limits for the cooler stack rather than the kiln stack apply to the raw mill vent.

### Air Pollution Control Measures

Upsets in the kiln can rapidly increase the vent gas temperature to 1000°F and the dust load to 13–50 gr/acf. In older plants, there may be bypass arrangements to vent these gases directly to the atmosphere until the upset is over. These particulate emission excursions are not permitted in newer plants. Gas temperatures are controlled to protect the dust collector through the use of tempering bleed air, water sprays, or an air-to-air heat exchanger. All these methods have costs and limitations, and there is no clear universal solution. In a few plants with air-to-air heat exchangers, cooled excess air is recirculated to the cooler, thereby eliminating the need for a clinker cooler vent stack.

The dust collectors used on reciprocating grate clinker coolers are most often fabric filters. ESPs and gravel bed filters are infrequently used. Sometimes clinker cooler dust collectors are preceded in the gas flow stream by a mechanical cyclone or multiclone dust collector. Typical fabric filters on clinker coolers are pulse jets or pulsed plenums in the newer plants and reverse-air types in the older plants (see Table 5).

## CLINKER STORAGE

### Process Description

To allow for necessary operational flexibility, a cement plant is usually able to store from 5% to 25% of its annual clinker production capacity. The storage requirement largely depends on the shipping cycle. Northern plants usually manufacture and store clinker during the inactive winter months for grinding during the summer shipping season.

The material-handling equipment used to transport clinker from the clinker coolers to storage and then to the finish mill department is similar to that used to transport raw materials (i.e., belt conveyors, screw conveyors, deep-bucket conveyors, and bucket elevators). Drag chains are sometimes used because they are less sensitive to abrasion and high temperatures during upset conditions. Gravity drops and transfer points in the conveying and storage systems are normally enclosed and vented to dust collectors.

Older plants were typically designed to store clinker in partially enclosed buildings and storage halls or in outside piles. Newer and modernized plants store at least some clinker in fully enclosed storage halls or cylindrical, vertical silos. Clinker storage domes are gaining in popularity.

### Air Emissions Characterization

Dust in the clinker has a tendency to become airborne during handling. The character of the dust varies by plant and existing process conditions. Dust caught in the clinker cooler exhaust dust collector is often returned to the clinker stream and can result in reentrainment of this material in air during subsequent handling. Clinker dust is normally a small proportion of clinker production and is relatively coarse, but some kilns normally produce dusty clinker. During process upsets when the kiln falls below clinkering temperatures and runs "raw," material that is discharged from the kiln is said to be "unburned" (i.e., not fused into clinker) and is very dusty.

### Air Pollution Control Measures

The air pollution control measures and equipment used in clinker handling systems are similar to those described for raw milling.

The free fall of clinker onto storage piles usually creates visible, fugitive particulate emissions. This dust generation can be reduced by discharging the clinker to piles through a simple device known as a rock ladder or by using variable-height, stacker belt conveyor systems. Water sprays are incompatible with clinker dust. However, fugitive dust emissions from the surface of open clinker storage piles are mitigated by precipitation, which causes a crust to form on the piles. Wind breaks and pile covers (e.g., tarpaulins) have also been used to minimize fugitive clinker dust with mixed success. Clinker in open piles is usually reclaimed with mobile equipment, such as front-end loaders. Clinker in storage halls is frequently

**Table 5. Fabric Filters on Clinker Coolers**

| | Pulsed Plenum/Pulse Jet | Reverse Air | Precipitator |
|---|---|---|---|
| Acfm | 20,000–100,000 | 20,000–100,000 | 20,000–100,000 |
| Filter design | Tubular bag | Tubular bag | N/A |
| Filter type | Nomex, polyester | Nomex, fiberglass | N/A |
| Temp.(°F) | ≤400, <275 | ≤400, <500 | 350–600 |
| A/C ratio[a] | ≤5:1 net | 2:1 net | SCA: 350–500[b] |
| Inlet loading (gr/acf) | 5–10 | 5–10 | 5–10 |
| Outlet emission (gr/acf) | 0.02 | 0.02 | 0.02 |

[a] Air-to-cloth ratio (acfm/ft$^2$).

[b] Specific collecting area (ft$^2$/1000 acfm).

handled with overhead bucket cranes. Fugitive clinker dust originating from material handling operations around open storage piles is often observed and is very difficult to control.

## FINISH MILLING

### Process Description

The final step in the manufacture of portland cement is the grinding of clinker to a fine powder. Up to 5% by weight of gypsum and/or natural anhydrite is added to the clinker during grinding to control the setting time of the cement. In the industry, this step is called finish grinding or milling and is accomplished in the finish mill department. Small amounts of various other chemicals may be added to the cement during finish grinding to function as processing additions (e.g., grinding aids) or to impart special properties to the cement or resulting concrete (e.g., air entrainment). Small amounts of water are often sprayed into a cement finish mill to aid in cooling the mill and the cement. Other specification and nonspecification cements with unique properties and constituents can be prepared in the finish mill department. For example, pozzolans or blast furnace slag can be mixed with portland cement clinker and gypsum during the finish grinding process to produce blended cements. In the United States, a common speciality cement derived from portland cement clinker is masonry cement. Typically, a masonry cement is composed of equal portions of portland cement clinker and limestone to which 2–4% by weight of gypsum is added. In addition, chemicals that impart the properties of air entrainment, plasticity, and water repellency to a mortar are added. Each manufacturer of masonry cement has a proprietary formula for its product.

Finish milling is almost exclusively accomplished in ball or tube mills. These mills are rotating, horizontal steel cylinders containing slightly less than half their volume in steel alloy balls, which are called grinding media. These balls can range in size from 4 to $\frac{1}{2}$ in. in diameter. Clinker and gypsum are introduced into the feed end of the mill, and partially ground portland cement exits from the discharge end. A finish mill might be divided into two or more internal compartments in which the grinding media are segregated by size. The larger balls are at the feed end of the mill. The compartments of the mills are formed by slotted division heads that are perpendicular to the mill's longitudinal axis and cover the entire circular cross section of the mill. The slots are small enough to retain the grinding media in the proper compartment, but large enough to allow the partially ground cement to flow toward the discharge end. At the discharge end of the mill, there is a similar slotted barrier called a discharge grate that serves to keep the balls in the mill while allowing partially ground cement to exit. A given particle of cement remains in the mill for 3–7 min. The ends (heads) and sides (shells) of the mills are lined with replaceable alloy steel plates or castings that undergo the wear and abrasion of the grinding process. Mill shell linings are sometimes designed so that the balls are segregated by size during mill operation, thereby eliminating the need for division heads.

Cement is usually ground in a closed circuit with an air separator. This continuously operating device is used to separate particles of cement of acceptable size in the material discharged from the mill from those particles that have not been fully ground. The large particles (i.e., tailings) are returned to the mill and reintroduced to the feed end along with new feed. A figure that is 100 times the ratio of the weight of the returned tailings to the weight of new feed is called the circulating load and is expressed in percent. Circulating loads in the range of 200–500% are typical, but higher and lower circulating loads are found in acceptable mill circuits. Air separators are mechanical devices that use centrifugal force, gravity, and an ascending air current to separate the cement particles. Older air separators have a relatively low separation efficiency. Equipment manufacturers now offer high-efficiency separators that are included in most new finish mill projects and are popular retrofit items because of the increased efficiency, lower operating costs, and improved product performance.

Another device of increasing popularity in the finish mill department is the roll crusher. This device accomplishes the initial size reduction of the clinker and the gypsum outside and prior to the ball mill. The efficiency and/or the productive capacity of a given ball mill is thereby increased at potentially lower grinding temperatures.

For a variety of reasons, cement customers usually demand cement that is at temperatures of 100–150°F when delivered. Cement grinding temperatures can reach 350°F. The high-efficiency separator circuits, with their associated high volumes of mill vent air, provide better cooling of the cement than conventional mill circuits. Water-supplied cement coolers (i.e., heat exchangers) are often installed in the material flow path following the finish mill to reduce the cement temperatures prior to product storage. No air pollution problems are associated with the fully closed cement coolers.

Figure 9 is a process flow sheet for a finish mill circuit that includes a roll crusher and a high-efficiency air separator. Figure 10 shows a two-compartment ball mill in finish mill service as viewed from the feed end of the mill.

### Air Emissions Characterization

Particulate emissions from mill vents, air separator vents, and material-handling system vents constitute the air pollution concerns in the finish mill department.

About 30–40% of the particles of ordinary Type I portland cement are finer than 10 μm. For Type III, high-early-strength portland cement, the percentage of particles finer than 10 μm increases to the 45–65% range. Typically, about 90% of portland cement will pass a 325-mesh (44-μm) sieve. The potential air pollution problems associated with the manufacture, handling, and transportation of portland cement have their origin in the large proportion of very fine particles in the product.

### Air Pollution Control Measures

Emissions from finish mills are controlled adequately by fabric filters. The fabric filters most often found on new or upgraded plants are the pulse-jet and pulsed-plenum types. Reverse air/shaker fabric filters are typically found in older plants. In almost all cases, pulse-jet or pulsed-plenum fabric filters are installed in conjunction with high-efficiency separators (see Tables 6 and 7).

The cement dust caught in a fabric filter is returned to the process. In colder weather, the water that is used for internal mill cooling can produce a steam plume at the mill baghouse vent. This plume is sometimes confused with excessive particulate emissions, but it will dissipate within the gas temperature is about 1800°F to achieve a beneficial reaction between ammonia and $NO_x$. To date, this technology, selective noncatalytic reduction (SNCR), has not been used on a continuous basis in the United States. Ammonia injection does not appear to be possible in pyroprocessing systems with only a rotary kiln, since the point of optimum temperature is not accessible through the rotating kiln shell. Other possibilities for $NO_x$ emissions reduction exist in the recirculation of flue gas as oxygen-deficient primary air in the rotary kiln, alternative or low-nitrogen fuels and/or raw materials, and mid-kiln injection of used tires or other combustible solids as a supplementary fuel.

## CLINKER COOLING

### Process Description

The clinker produced in a rotary kiln is cooled in a device called a clinker cooler. This process step recoups up to 30% of the heat input to the kiln system, locks in desirable product qualities by freezing mineralogy, and makes it possible to handle the cooled clinker with conventional conveying equipment.

Depicted in Figure 8 is the predominant type of clinker cooler, the reciprocating grate, in which clinker is cooled from about 2000°F to 250°F by ambient air passing through a horizontal bed of clinker. A portion of the resulting hot air is used as combustion air in the kiln. Cooling air not utilized in the rotary kiln for combustion is vented to the atmosphere, used for drying coal or raw materials, or used as a source of heated combustion air in a precalciner. If necessary to further reduce clinker temperature, secondary coolers with direct or indirect air to clinker contact may be employed. If necessary, air from these clinker coolers is vented to atmosphere through fabric filters.

The reciprocating grate cooler consists of a horizontal box of rectangular cross section that houses horizontal rows of fixed and movable grate plates that bisect the cross section. A typical grate plate has multiple passages for air and is about 1 foot square. A row of grate plates is perpendicular to the flow of the clinker and may consist of 6–12 grate plates, depending on the cooler capacity. The clinker cooler is normally oriented so that the clinker continues its flow in line with the longitudinal axis of the kiln as it moves along the top of the grates. Typically, the reciprocating movement of every second row of grates forces the clinker through the cooler. Other methods to move the clinker through the cooler are being introduced by equipment vendors. Ambient air is forced through the grates and the bed of clinker from the chamber below by a series of fans along the length of the cooler.

Only a portion of the air supplied to a reciprocating grate cooler will be used for combustion air in the kiln, combustion air in the calciner, or hot air for the coal or raw mills. The excess air must be cleaned of clinker dust before it is vented to the atmosphere.

### Air Emissions Characterization

The collected dust from clinker coolers is fairly coarse, with only about 0–15% of it finer than 10 μm. This abrasive dust

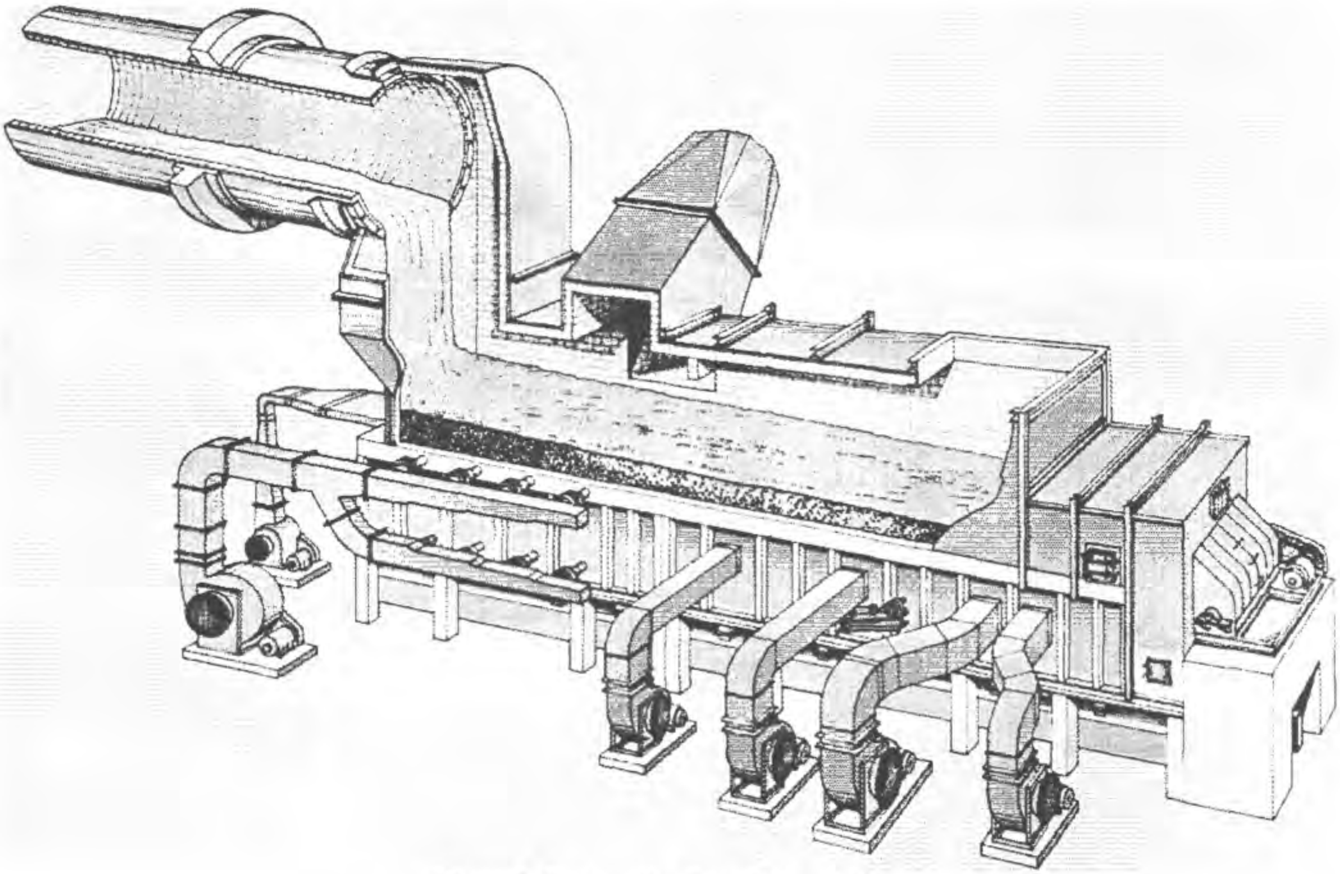

**Figure 8.** Reciprocating Grate Clinker Cooler.

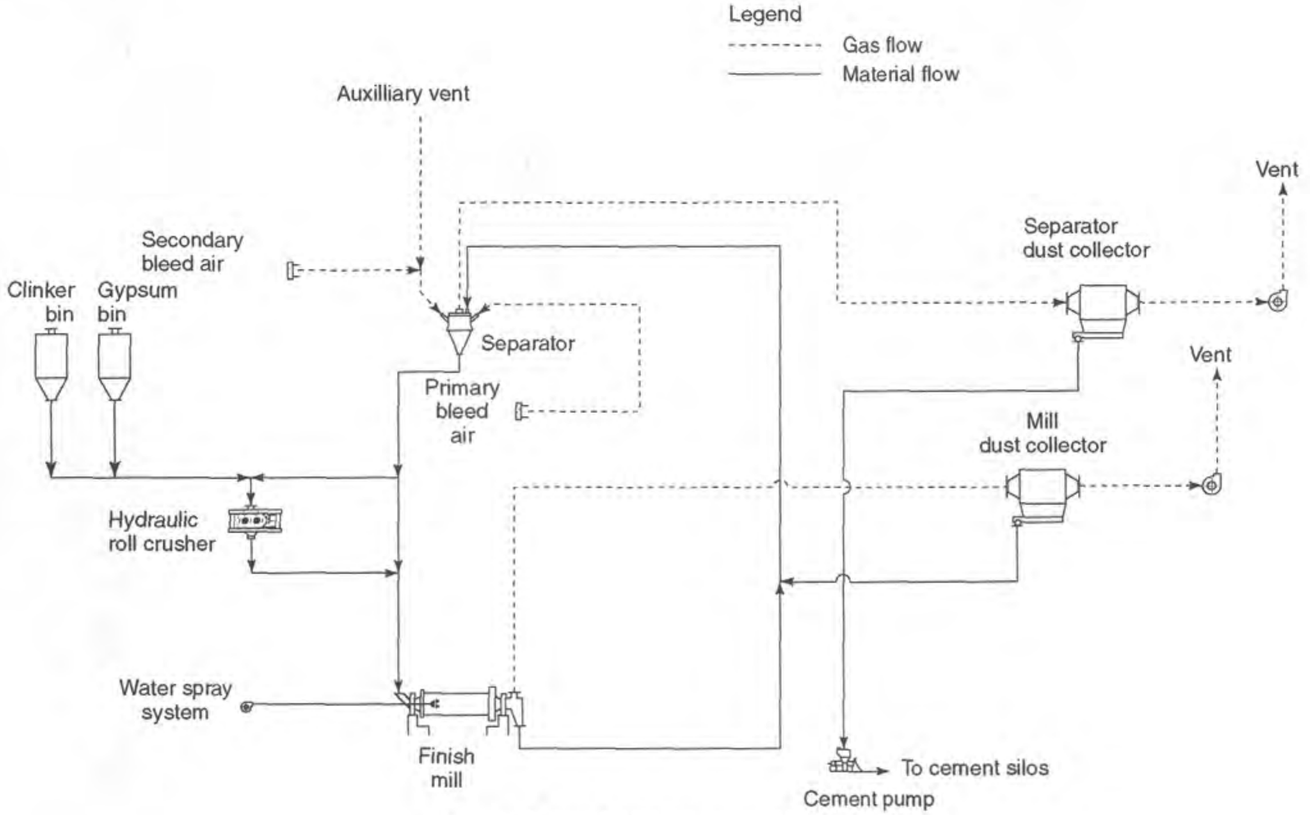

**Figure 9.** Finish Mill Schematic Diagram.

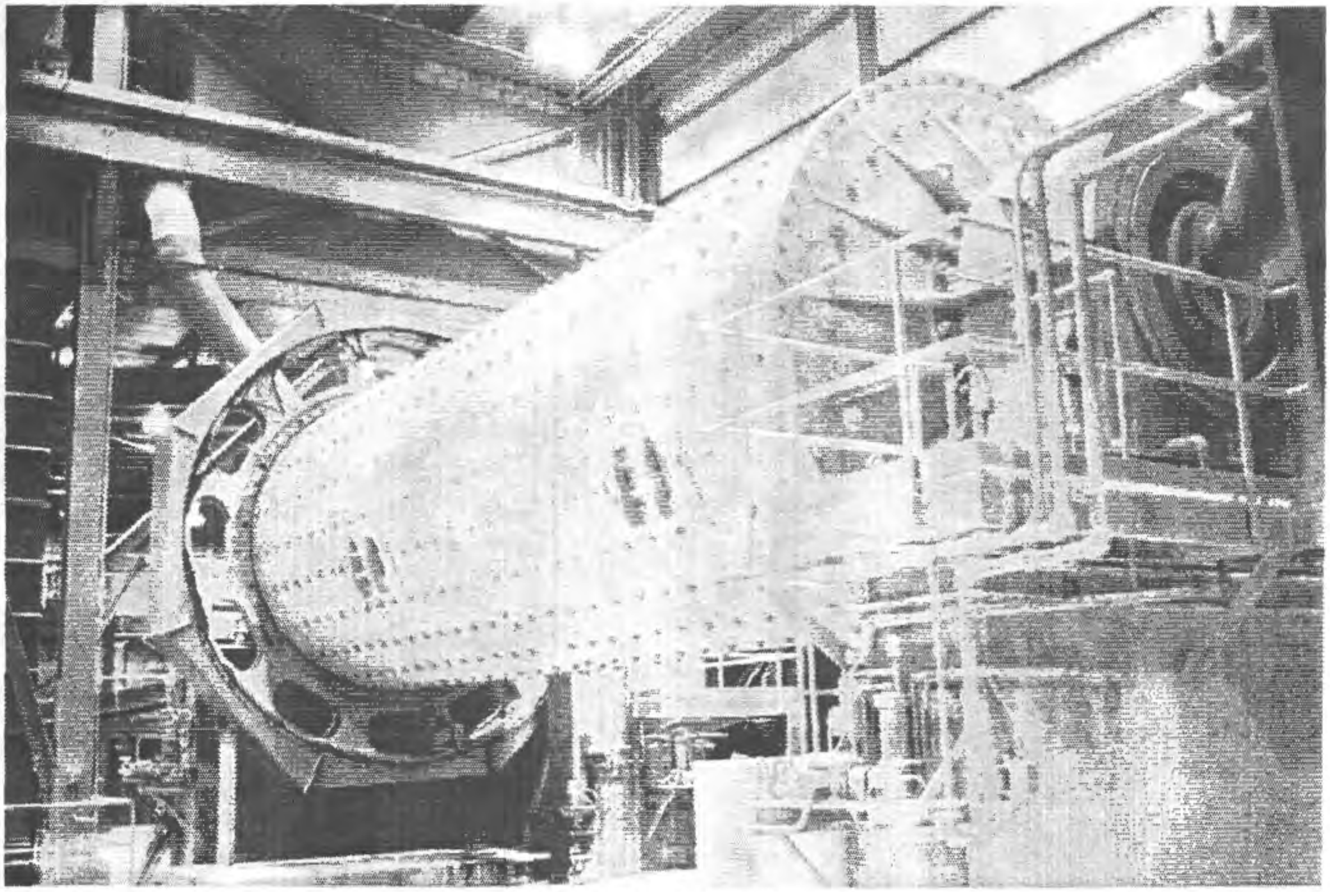

**Figure 10.** Finish Mill.

**Table 6. Fabric Filters for Finish Mill Systems**

| | Reverse Air/Shaker | | Pulse Jet | | Pulse Plenum |
|---|---|---|---|---|---|
| Acfm | 10,000–30,000 | 10,000–30,000 | 10,000–30,000 | 10,000–30,000 | 10,000–30,000 |
| Filter design | Tubular bag | Pleated | Tubular bag | PTFE membrane on tubular bag | Tubular bag |
| Filter type | Polyester | Spun-bonded Polyester | Polyester | Polyester with PTFE membrane | Polyester |
| Temp.(°F) | ≤275 | ≤265 | ≤275 | ≤275 | ≤275 |
| A/C ratio[a] | ≤2.5:1 | ≤2.5:1 | ≤4:1 | <5:1 | 4:1 |
| Inlet loading (gr/acf) | 5–20 | 5–100 | 5–100 | 5–100 | 5–100 |
| Outlet emission (gr/acf) | 0.02 | <0.01 | <0.02 | 0.005 | 0.02 |

[a] Air-to-cloth ratio (acfm/ft$^2$)

**Table 7. Fabric Filters for High-Efficiency Separators**

| | Pulse Jet | | | Pulse Plenum |
|---|---|---|---|---|
| acfm | 40,000–60,000 | 40,000–60,000 | 40,000–60,000 | 40,000–60,000 |
| Filter design | Pleated | Tubular bag | PTFE membrane on tubular bag | Tubular bag |
| Filter type | Spun-bonded polyester | Polyester felt | Polyester with PTFE membrane | Polyester |
| Temp.(°F) | <265 | <275 | <275 | <275 |
| A/C Ratio[a] | <2.0:1 | <4.0:1 | <5.0:1 | ≤3.5:1 |
| Inlet loading (gr/acf) | 150–300 | 150–300 | 150–300 | 150–300 |
| Outlet emission (gr/acf) | <0.01 | <0.02 | <0.005 | 0.02 |

[a] Air-to-cloth ratio (acfm/ft$^2$).

a few feet of the vent opening. Fabric filters on finish mill systems that use cooling water must be well insulated to prevent condensation within the baghouse and subsequent blinding of the bags.

## PACKING AND LOADING

### Process Description

Portland cement is pneumatically conveyed from the finish mill department to large, vertical, cylindrical concrete storage silos in the packhouse or shipping department. Storage domes are coming into use. Mechanical transfer systems, such as bucket elevators, belt conveyors, screw conveyors, and air-slide conveyors, supplement the pneumatic system.

The number and capacity of the storage silos or domes depend on the capacity of the plant, the number (i.e., types) of cements in the product mix, the marketing strategy of the company, and the weather-driven shipping pattern.

Portland cement is withdrawn from the storage silos or domes by a variety of feeding devices and conveyed to loading stations in the plant or directly to transport vehicles using the same kinds of material-transfer systems that were used to put the cement into the silos. Most of the portland cement is shipped from the plant in bulk by rail or truck transport. Those plants located adjacent to water transportation routes usually serve some customers or distribution terminals by barge or ship.

Portland cement is also shipped in multiwall paper bags with a capacity of 94 pounds. These bags are filled on automatic or semiautomatic packing machines. During filling, each bag is vented to a bag filter to allow the escape of displaced air. The filled bags are then manually or mechanically palletized for shipment.

Masonry cement is almost totally shipped in multiwall paper bags. Bag weights range from 70 to 80 pounds, depending on the type of masonry cement in the bag. The packing, palletizing, and dust suppression operations are identical to those used for portland cement.

There are remote distribution terminals associated with some cement plants. Bulk or packaged cement is shipped in advance from the plant to the terminal to provide subsequent timely distribution to customers. Terminals are most often supplied by rail or barge shipments, although trucks and ships are sometimes used. The handling and loading of bulk portland cement at distribution terminals are carried out by the same kinds of pneumatic and mechanical conveying systems as are used at the plant.

### Air Emissions Characterization

Particulate emissions from the silo openings, cement-handling equipment, bulk and package loading operations, and the fabric filters constitute the air pollution concerns in the shipping department.

### Air Pollution Control Measures

Active and passive fabric filters are used to remove dust from the exhaust airstreams from the silos, domes, transport systems, and packaging operations. The cement dust is returned to the product.

The dust generated during the loading of trucks, railcars, barges, and ships is controlled by venting the transport vessel to a fabric filter. The collected dust is returned to the shipment of cement. Flexible loading spouts with concentric pipes are among the devices that are successfully used for dust-free loading. In a loading spout, the cement flows to the transport vessel by gravity through a central pipe, while air displaced from the transport vessel is drawn through an annular space.

Dust is controlled at distribution terminals through the venting of silos, bins, and transfer points to fabric filters. The captured cement dust is returned to the product.

The typical fabric filters used in the packing and loading departments of newer plants are of the pulse-jet type. Reverse-air or shaker-type fabric filters are found in older plants. Occasionally, a cartridge-type fabric filter will be employed (see Table 8).

## SUPPLEMENTAL FUELS AND RAW MATERIALS

The recycling of wastes of other industries in portland cement kilns as fuel and raw material substitutes is a reliable and proven technology. This technology offers a safe, cost-effective and environmentally sound method of beneficial recovery of the energy and chemical values of selected wastes, thereby enabling a portland cement manufacturer to operate at lower cost.

The energy-bearing, ignitable wastes that are currently used in the portland cement industry as fossil fuel substitutes are waste oils, spent organic solvents, paints, organic sludges, and other combustible residues from the chemical, manufacturing, and petroleum industries. Smaller amounts of other waste streams are also being successfully recycled into cement kilns as fuel substitutes. Some waste streams require preparation so that they can be effectively introduced into the kiln. For example, liquids with high or variable chlorine levels are blended with other waste liquids to provide a lower or more consistent chlorine concentration in the waste-derived fuel (WDF). Sludges are liquefied, solidified, or encapsulated to provide better material-handling properties. Solids also may be ground to facilitate blending into liquid fuels. Materials such as sawdust can be handled with the same equipment as coal and are readily consumed in a cement kiln. Other high-energy waste streams, such as used rubber tires, are finding increased acceptance as fossil fuel substitutes.

The greatest economic and societal benefits from utilizing wastes in cement manufacturing are derived from the replacement of fossil fuel. Coal and petroleum coke provide about four-fifths of the thermal energy for manufacturing cement in the United States. In 1997, the portland cement industry obtained about 28 trillion Btu or 9.6% of its thermal energy requirements from waste-derived fuels. Higher substitution rates are technically possible.

Older, less fuel-efficient cement plants often derive the greatest economic benefit from waste fuel substitution because of their higher demand for fuel. These older facilities can successfully compete with more modern facilities as a result of lower operating costs and improved cash flow when fossil fuel is replaced with a cheaper substitute.

Cement kilns have several important characteristics that contribute to the effective destruction of organic waste materials. The gas residence time in the burning zone of the kiln at 3000°F or higher is approximately 3 sec. Temperatures in excess of 2000°F exist for as long as 6 sec. Test burns have repeatedly demonstrated destruction and removal efficiencies (DREs) of 99.99–99.9999% for even the most stable organic compounds.

Constituents of ash resulting from incombustible constituents in any waste (e.g., metals) primarily becomes chemically incorporated into the clinker crystal matrix or is caught with the CKD in the air pollution control device prior to the kiln stack. The more volatile metals (e.g., lead) migrate to the CKD, while refractory metals (e.g., chromium) are mostly found in the clinker. Since cement raw materials come from the earth's crust, lead and chromium, and other naturally occurring trace metals, are found in all cement and CKD. The use of waste-derived fuels and waste raw materials may increase the metal content of cement and CKD by small increments. No matter the source, however, metals emissions from cement kilns can be controlled to meet applicable environmental standards. The chemical and physical specifications for the performance of portland cement also make it necessary for a cement manufacturer to monitor the input of several trace elements that can be found in substitute fuels and raw materials.

An excessive chlorine input can contribute to material buildups within a pyroprocessing system (e.g., kiln rings), deterioration of ESP performance, and excessive corrosion of pyroprocessing system components. A cement manufacturer quickly learns the maximum chlorine feed rate that a

**Table 8. Fabric Filters in Packing and Loading Department**

| | Pulse Jet | | | Pulse Plenum |
|---|---|---|---|---|
| Acfm | 3,000–10,000 | 3,000–10,000 | 3,000–10,000 | 3,000–10,000 |
| Filter design | Pleated | Tubular bag | PTFE membrane on tubular bag | Tubular bag |
| Filter type | Spun-bonded polyester | Polyester | Felt with PTFE membrane | Polyester |
| Temp.(°F) | ≤265 | ≤275 | ≤275 | <275 |
| A/C ratio[a] | ≤3.5:1 | ≤5.0:1 | ≤5.5:1 | ≤2.5:1 |
| Inlet loading (gr/acf) | 5–40 | 5–40 | 5–40 | 5–40 |
| Outlet emission (gr/acf) | <0.01 | <0.02 | <0.005 | 0.02 |

[a] Air-to-cloth ratio (acfm/ft$^2$).

pyroprocessing system will tolerate and limits chlorine input from natural fuel and raw materials or waste substitutes to less than that amount. In addition, the feed rate of chlorine to each kiln using hazardous WDF is limited by regulatory constraints. Regulations for burning hazardous WDF in cement kilns were promulgated under RCRA by the EPA on February 21, 1991. The air emissions of pollutants of concern (i.e., CO, hydrocarbons, hydrogen chloride, and heavy metals) during waste burning for energy recovery are regulated under these regulations.

The cement-making process offers many unique opportunities for the utilization of noncombustible solid wastes. Silicon, aluminum, and iron are needed to react chemically with the calcium in the cement raw mix. Materials such as spent cracking catalyst, diatomaceous-earth filter media, foundry sand, and steel mill scale have high concentrations of these elements and are used to replace the conventional siliceous, argillaceous, and ferriferous components of the raw mix.

## HAZARDOUS AIR POLLUTANTS

Two National Emission Standards for Hazardous Air Pollutants (NESHAPs) affecting the portland cement manufacturing industry are expected to be promulgated in 1999. The first of these standards applies to all operations in all cement plants and can be found at 40 CFR 63, Subpart LLL. The second standard only applies to the pyroprocessing emissions from those plants burning hazardous WDF and can be found at 40 CFR 63, Subpart EEE.

## PROCESS AND QUALITY CONTROL

Modern cement plants are exclusively controlled by digital computers from central control rooms. Process variables in all manufacturing departments are continuously monitored. Usually, process control actions are initiated by the process control computer, but manual intervention is possible during process upsets, equipment malfunctions, or emergency conditions. Older cement plants use analog control systems in either central control rooms or departmental control stations.

Modern cement plants are usually equipped with continuous opacity monitors on the kiln and clinker cooler stacks. At many plants, gaseous emissions of oxygen, CO, $NO_x$, and $SO_2$ from the kiln stacks are also continuously monitored. These monitoring devices are reliable. Nevertheless, equipment redundancy may be required if there are to be minimal data gaps in a compliance-monitoring scheme. The location of these devices in the process is often hot and dirty, thereby complicating the monitoring task.

The portland cement process involves rather complex chemistry and requires close process control. Plant laboratories are staffed around the clock. Frequent chemical and physical tests are made on raw materials, raw mix, clinker, and cement. The procedures may range from elementary wet chemistry to more sophisticated testing by X-ray fluorescence. The newest cement plants are equipped with automatic sampling and analytical systems. The operation of the pyroprocessing system receives particularly close attention since product quality is largely determined in the kiln. If proper process conditions and kiln temperatures are not maintained, the complex chemical reactions that take place in the kiln are incomplete and the clinker is unacceptable. Catastrophic and expensive failure of the process can also occur.

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## CERAMIC AND BRICK MANUFACTURING

Dennis A. Brosnan

Ceramic and brick products are considered "traditional" ceramics because of their long history of manufacture using well-known techniques of powder processing and a high-temperature processing step, known as firing, with the latter process to develop a permanent bond between residual particles in the composition. Traditional ceramic products contain clay minerals as a significant part of their composition. The clay functions in the product-forming stage to provide plasticity and cohesion in the powder mass and in the firing step as a precursor to formation of vitreous (glassy) phases, which, on cooling, provide for a permanent bond and for the useful properties of the product.

Ceramic products include wall and floor tile, which are generally made by powder pressing techniques, and