

ACI 130R-19

Report on the Role of Materials in Sustainable Concrete Construction

Reported by ACI Committee 130



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Report on the Role of Materials in Sustainable Concrete Construction

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Report on the Role of Materials in Sustainable Concrete Construction

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Concrete has general properties, including versatility, resilience, durability, and relatively low cost, that make it the most widely used building material in the world. Architects, engineers, researchers, and concrete practitioners have immeasurable opportunities to incorporate sustainable development into their selection of materials for the manufacture of concrete. The immediate and direct connection between sustainable development and concrete materials

includes efficient use of materials (conservation, substitution, reuse, repurposing, and recycling), materials life-cycle assessment, replacement materials (scarcity, resource availability, and materials economics), energy (materials to support alternative energy technologies, to mitigate problems with fossil-fuel technologies, and to increase energy efficiency), mitigation of undesirable environmental impacts from technology and economic growth (corrosion, pollution, and toxic waste), and water purification. Information is presented to assist in the development of practical knowledge and selection of materials used in concrete manufacture.

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Keywords: admixtures; aggregates; blended cement; non-portland binders; portland cement; recycled aggregates; reinforcing steel; supplementary cementitious materials; waste reduction; water.

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CHAPTER 1—INTRODUCTION AND SCOPE**1.1—Introduction**

Concrete is defined as a mixture of hydraulic cement, aggregates, and water, with or without admixtures, fibers, or other cementitious materials. The main ingredients of concrete by mass are aggregates, constituting up to 80 percent of the total, followed by the cement and other cementitious

materials, typically between 7 and 12 percent by mass. The balance is made up of water and small amounts of other additives and chemical admixtures. The environmental footprints of these ingredients are different and are discussed in detail in **Chapter 3**. Recall that the beneficial performance of concrete is fully realized by the satisfactory design and detailing of a structure; appropriate mixture proportions; proper production, placement, and curing of concrete; and timely maintenance and repair.

Concrete is used throughout the world in many applications in construction. Historically, many civilizations used concrete and masonry in their structures. One often-cited example is the Roman Pantheon, which has been standing for nearly two millennia. Today, concrete is a versatile material, allowing a large range of shapes, textures, and structural applications. Concrete is a durable and economical material when proportioned, manufactured, and installed properly.

Its use in designing long-life structures enables the construction of housing and infrastructure that contributes to environmental protection and the assurance of public safety, health, security, serviceability, and life-cycle cost-effectiveness.

For nearly two centuries, portland cement has been used to produce concrete. Modern cement production began with the patent for portland cement manufacturing issued to Joseph Aspdin in England in 1824. From small batches of cement in beehive kilns to today's more efficient rotary kilns with worldwide output of over 4.5 billion tons (4.1 billion metric tons) of cement (**USGS 2018**), the impact of cement production on natural resources and energy use is significant. With increasing societal demands placed on resource and energy conservation, sustainable concrete production and diligent use of materials are required for construction of the built environment.

Improvements in cement production, such as development of efficient kiln technology and the use of both alternative raw materials and alternative fuels, have resulted in significant advancements in concrete sustainability. These changes have also reduced the consumption of virgin raw materials and fossil fuels. Further, concrete production has embraced as common practice the use of reclaimed water, such as wash water, and the use of reclaimed materials, such as cementitious materials or aggregates. Additionally, new technologies containing little or no portland cement are also being adopted. Aggregates are the largest portion of concrete by mass and volume, and the use of reclaimed aggregate materials have a significant impact on resource conservation. Other materials in concrete construction, such as reinforcing steel and fibers, also include a significant portion of recycled content or reclaimed material that can lower their environmental impact.

This document provides an overview of the materials commonly used in sustainable concrete construction, the benefits of their use, and how efforts to reduce the environmental impact of their production and use are evolving.

This document presents aspects of the material choices used in mixture proportioning and their impact on the sustainable nature of concrete.

1.2—Scope

This report deals with the sustainability aspects of materials selection in concrete production. **Chapters 3 to 7** address each of the major material components of a concrete mixture: cementitious materials, aggregates, chemical admixtures, mixture water, and reinforcement. The sustainability impacts of a concrete mixture depend not only on the materials selected, but on their proportioning. Materials selection can improve concrete sustainability through a range of metrics, including but not limited to reduced carbon impacts, enhanced material efficiency, improved construction practices, and extended service life. Information providing an overview of each category is presented with observed effects reported for each group of materials. The wide scope of concrete materials, the continued development and introduction of new or modified materials, and the variations of effects with different concreting materials and conditions preclude a complete listing of all concrete materials and their sustainability impacts on concrete.

CHAPTER 2—DEFINITIONS

ACI provides a comprehensive list of definitions through an online resource, ACI Concrete Terminology.

CHAPTER 3—CEMENTITIOUS MATERIALS

3.1—Portland cement

The term ‘cement’ is usually associated with portland cement, the most common hydraulic cement. Although the use of lime and pozzolans to produce concrete and masonry dates back to the Roman Empire, the invention of portland cement is relatively recent. It is credited to Joseph Aspdin, a builder from Leeds, England. In 1824, he was awarded a patent for his process of grinding limestone, mixing it with finely divided clay, burning the mixture in a kiln, and finely grinding the resulting clinker. He gave his invention the name portland cement because of its resemblance to the natural building stone near Portland, England. This was the beginning of the modern cement industry, which in 2017 had an estimated world-wide production of 4.5 billion tons (4.1 billion metric tons), including both portland and blended cements (**USGS 2018**).

3.1.1 Cement manufacture and environmental impact—Concrete is expected to be strong, durable, safe, versatile, and economical in all forms of construction, supporting communities and infrastructure. Hydraulic cement is the most important ingredient that gives concrete these qualities. Concrete has demonstrated its longevity, which is one factor that contributes to sustainability, retaining its engineering properties for decades. With present technology, concrete is being used in 100-year-service-life structures in severe exposure conditions.

As with all manufacturing processes, cement manufacture has environmental impacts that in turn affect the environmental impact of concrete. The manufacture of cement is an energy-intensive process. Raw ingredients are mined and then ground, blended, and heated to approximately 2640°F (1450°C). As a result of heating to this temperature, chem-

ical reactions take place and form the mineral phases of portland cement clinker. After cooling, clinker is then ground with a small amount of gypsum to regulate setting time. In the United States, cement manufactured according to **ASTM C150/C150M** may also contain ground limestone and processing additions to produce portland cement. Regional specifications such as **BS EN 197-1:2011** include a wide range of cement types and allowable constituents.

In portland cement production, the primary environmental impact is typically considered to be carbon dioxide (CO₂) emissions. CO₂ is classified as a greenhouse gas (GHG), is naturally found in the atmosphere, and is an end-result of fuel combustion. In addition, during the pyroprocessing of cement raw ingredients, calcination of limestone occurs. Calcination is the process of converting calcium carbonate (CaCO₃) to calcium oxide (CaO), releasing CO₂ in the process. Approximately 40 percent of the CO₂ emitted during pyroprocess is due to fuel combustion, with the remaining 60 percent driven off of the limestone during calcination (**Marceau et al. 2007**).

In 2016, the Portland Cement Association published an Environmental Product Declaration (EPD) that estimated the cradle-to-gate carbon intensity of cement in the United States to be 1.040 units of CO₂ per unit of cement (**PCA 2016**). The percentage of total annual CO₂ from cement production can fluctuate based on total CO₂ emitted and cement production levels. In 2010, the **U.S. Environmental Protection Agency (EPA) (2012)** data showed the portion of total CO₂ from cement production in the United States to be approximately 1 percent, as shown in Fig. 3.1.1. A 2016 study of the global carbon budget estimated that cement production accounts for 5.6 percent of anthropogenic CO₂ released globally (**Le Quéré et al. 2016**).

Although CO₂ makes up a significant portion in GHG emissions, other compounds such as methane (CH₄) and nitrous oxide (N₂O) are also considered in assessing environmental impacts of a material. The combined impact of GHG emissions is commonly referred to as CO₂ equivalents, or CO₂e. CO₂e is a measurement used to normalize the emissions from various greenhouse gases based on their global warming potential (GWP). CO₂e are commonly expressed as terragrams of carbon dioxide equivalents (a terragram is 1 million metric tons). The CO₂e for a gas is derived by multiplying the tons of the gas by its associated GWP, thus: $TgCO_2Eq = (Gg \text{ of gas}) \times (GWP) \times (Tg/1000Gg)$. (**Environmental Protection Agency 2012**). For example, the GWP of CH₄ is 24; that is, the impact of unit mass of CH₄ may have a similar impact on global warming over 100 years as 24 units mass of CO₂.

3.1.2 Improving cement manufacturing energy and environmental efficiency—The manufacturing of any construction material results in environmental impacts. Consequently, manufacturers and researchers of cement have invested time and funding to reduce the impact of cement production while maintaining the expected performance of concrete. Impact reductions are found in several categories, including pyroprocessing and material processing (grinding/blending) cement formulations, and the inclu-

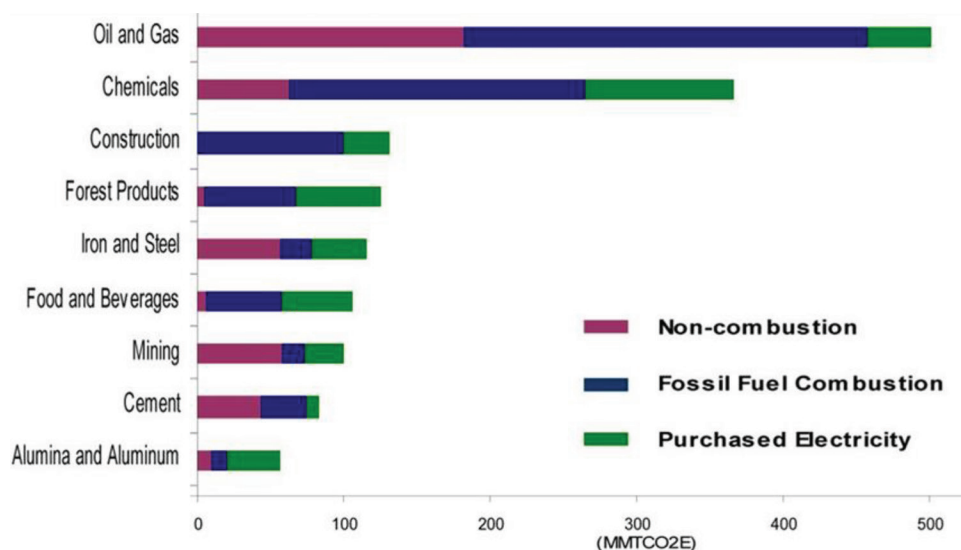


Fig. 3.1.1—Quantifying greenhouse gas emissions from key industrial sectors in the United States (Environmental Protection Agency 2008). (Note: Contribution to CO₂e by manufacturing process segment per sector.)

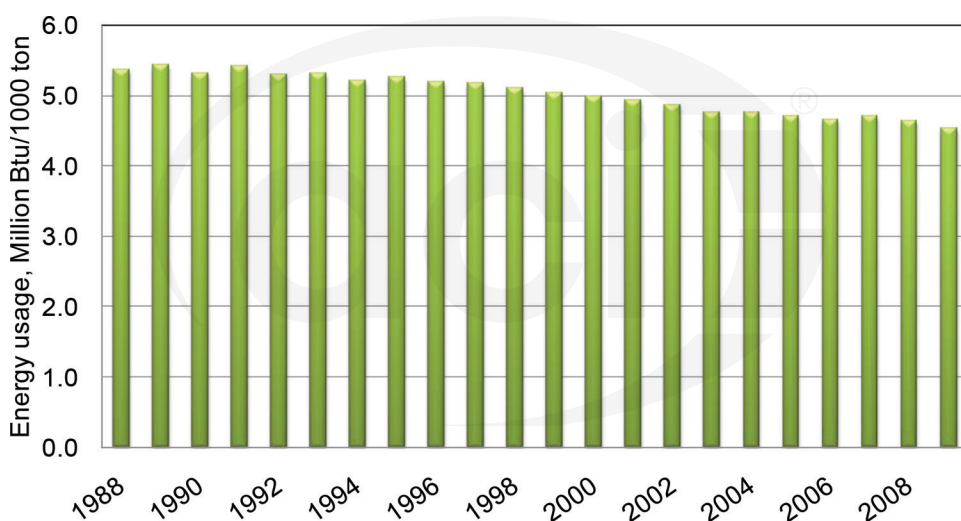


Fig. 3.1.2—Energy consumption data for U.S. cement industry from 1988 to 2010 (Portland Cement Association 2011).

sion of alternative energy and raw material sources. Each of these options provides positive benefits, with potential side effects in reducing environmental impacts for a given level of concrete performance:

- (a) Shifts from wet kilns to dry kilns
- (b) Capturing what was considered waste heat through preheater/precalciner technology
- (c) More efficient grinding processes
- (d) Use of alternative fuels ordinarily considered as by-products from consumers and other industries; over 65 percent of U.S. cement plants integrate alternative fuel into their energy consumption strategy according to the [Portland Cement Association \(2011\)](#)
- (e) Bio-fuel use based on recent energy research and pilot projects and carbon sequestration ([Business World Magazine 2012](#)), as well as harvesting wind energy ([Shafer 2009](#))

Figure 3.1.2 shows the energy required to produce 1 ton (0.907 metric tons) of clinker in the United States. Process improvements have resulted in a 40.1 percent reduction in energy consumption since 1972 (Portland Cement Association 2011).

Europe, for example, has a long tradition of producing blended hydraulic cements. Up to 85 percent slag has been used for many years, and over the last three decades, the use of fly ash blends and limestone as cement constituents has become common. Pozzolanic additions, such as perlite, have been common in Mediterranean countries for quite some time. Presently, most cements (19 of 27 types in [BS EN 197-1:2011](#)) in Europe are blended, and efforts are continuously being made to reduce the GHG contribution of hydraulic cement.

3.1.2.1 Use of alternative fuels and materials for cement manufacturing—Cement manufacturing uses some

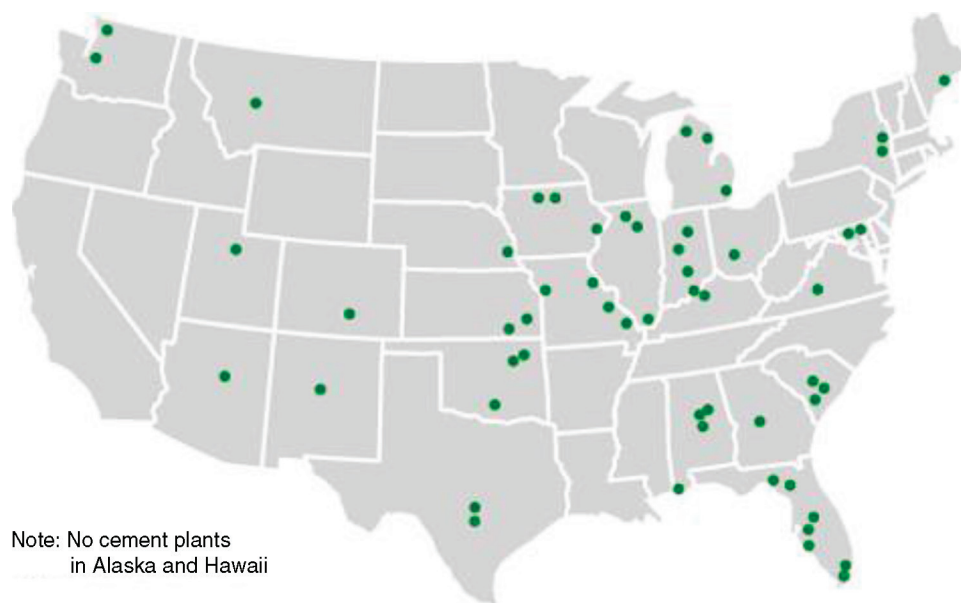


Fig. 3.1.2.1a—Portland cement plants that used blast-furnace or iron slag as a raw material in 2010 (Portland Cement Association 2011).

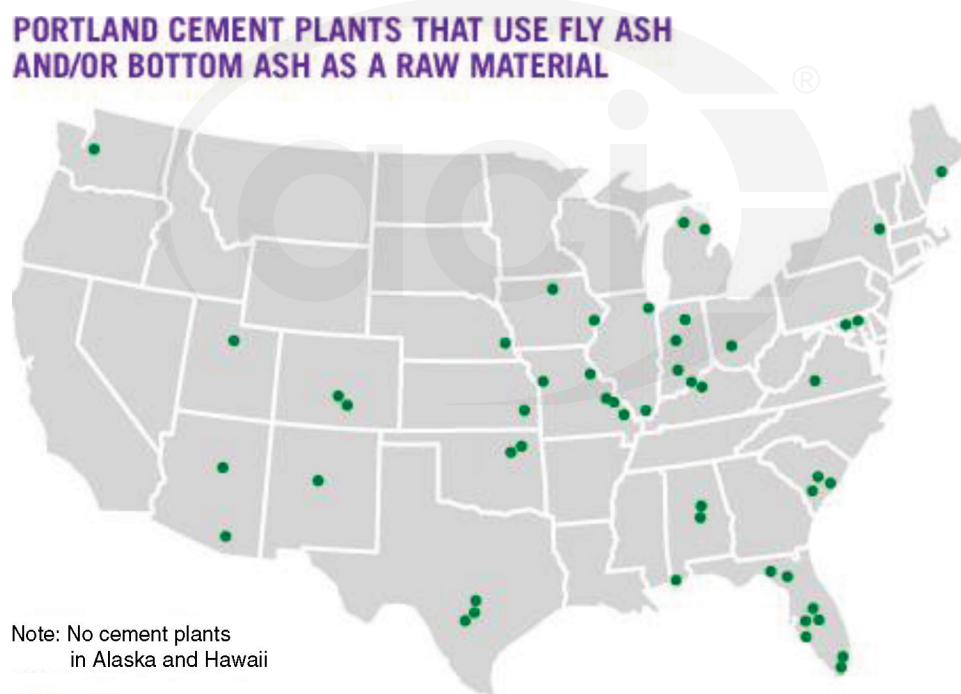


Fig. 3.1.2.1b—Portland cement plants that used fly ash and/or bottom ash as a raw material in 2010 (Portland Cement Association 2011).

by-product and recovered materials from other industries. Waste oils and scrap tires are commonly used as fuels in cement manufacture. Identified as an EPA Best Practice, the cement industry consumed 805,910 tons (731,109 metric tons) of scrap tires as fuel in 2017, according to the [Rubber Manufacturers Association \(2018\)](#). Forty-one of the 111 operating cement plants reporting in the United States in 2006 used blast-furnace or iron slag as a raw material ([Portland Cement Association 2011](#)); 50 plants used fly ash or

bottom ash from electric power plants (Portland Cement Association 2011) (Fig. 3.1.2.1a and 3.1.2.1b).

Other materials used in cement manufacturing include copper slag, foundry sand, mill scale, sandblasting grit, and synthetic gypsum. The high volumes of raw materials used to make cement and the detailed chemical analysis of raw materials allow for chemically-efficient and beneficial use of large volumes of these waste materials. These materials would otherwise be disposed of in landfills and, thus, their beneficial use in cement manufacturing reduces the volume

of these waste streams in addition to reducing the use of virgin materials.

3.1.2.2 Cement manufacturing and future planned actions—The U.S. cement industry committed to four major goals to improve its environmental impact ([Portland Cement Association 2011](#)). The first major goal with a voluntary target date of 2006 relates to environmental management systems (EMS):

(1) Environmental management systems—A target by 2010 that at least 75 percent of U.S. cement plants would have implemented an auditable and verifiable EMS rising to 90 percent by the end of 2020. PCA reported that by the end of 2010, 68 percent of the plants had implemented a program (Portland Cement Association 2011)

The three remaining industry goals adopted a voluntary target date of 2020 from a 1990 baseline to:

(2) Reduce CO₂ emissions by 10 percent per ton of cementitious product produced or sold

(3) Reduce by 60 percent the amount of cement kiln dust disposed in landfills per ton of clinker produced

(4) Improve energy efficiency by 20 percent as measured by total Btu-equivalent per unit of cementitious product

3.1.2.3 Specification revisions and potential reduction of environmental impacts—Changes in cement specifications have enabled further reductions in the environmental impact of portland cement in addition to those already achieved in the process area. In [ASTM C150/C150M](#) and [AASHTO M 85](#), two changes have had a significant impact: 1) permitting the use of up to 5 percent by mass of limestone to be used in cement; and 2) permitting use of up to 5 percent inorganic processing additions. In [ASTM C595/C595M](#) and [AASHTO M 240M/M 240](#), Type IL cement is permitted to use up to 15 percent limestone by mass. ASTM C595/C595M and AASHTO M240 ternary blended cement, Type IT, provides additional opportunities.

Similarly, in Canada, [CAN/CSA A3001](#) also allows up to 15 percent interground limestone in portland-limestone cements. These changes permit reduced amounts of clinker in finished cement, which reduces both the embodied energy and the GHG emissions related to cement manufacture ([Nisbet 1996](#)). Research on the characteristics and performance of cement with limestone demonstrated that equivalent performance in terms of strength, mechanical properties, plastic properties, and durability was achievable with these changes. A review of much of the existing work can be found in [Hawkins et al. \(2005\)](#) and [Tennis et al. \(2011\)](#).

3.1.2.4 Additional cement industry initiatives related to sustainability—The cement industry partners with multiple organizations devoted to improving the sustainability of cement manufacturing, including the World Business Council for Sustainable Development (WBCSD) Cement Sustainability Initiative (CSI) (3.1.2.4.1) and the Energy Star Cement Manufacturing Focus ([Energy Star 2014](#)).

3.1.2.4.1 World Business Council for Sustainable Development—WBCSD is an association of companies dealing exclusively with business and sustainable development. WBCSD supports companies in the exploration of sustain-

able development and the transfer of knowledge, experiences, and best practices. WBCSD focuses on four areas:

- (1) Energy and climate
- (2) Development
- (3) The business role
- (4) Ecosystems

The Cement Sustainability Initiative of the WBCSD is a subgroup of cement companies dedicated to addressing the sustainable development of cement. Approximately 70 percent of the U.S. clinker-producing cement plants participate in the WBCSD.

3.1.2.4.1 Energy Star Cement Manufacturing Focus—The U.S. Department of Energy and the EPA sponsor the Energy Star Industrial Focus Program. One aspect of this program is to assist businesses in overcoming barriers to energy efficiency by developing industry-specific energy management tools and resources. The Cement Manufacturing Focus began in 2003 and now includes over 65 percent of the clinker-producing cement plants.

3.1.2.5 White portland cement—White cement clinker is manufactured to limit the formation of compounds or minerals that darken the concrete. It can play an integral role in innovative sustainability strategies in numerous ways. Because the properties of white cement are essentially the same as gray cement, with the exception of its color, concrete made with white cement retains all the properties and durability of standard gray portland-cement concrete. Concrete made using white cement can deliver architectural benefits that eliminate the need for less durable or volatile organic compound-emitting surface-applied coatings or covering materials. White cement used in concrete facilitates a broad pallet of architectural colors and finishes, some of which would otherwise be unachievable with typical gray cements. In addition, slag cement or other light colored supplementary cementitious materials (SCMs) can maintain white appearance while improving sustainability by reducing portland cement use. Concrete produced with white hydraulic cement has significantly higher reflectance than gray cement concrete. For interior concrete applications, this can reduce lighting needs, potentially saving electrical power and reducing the cooling load of a building ([Portland Cement Association 2002](#)). In exterior applications, white cement concrete's higher reflectivity reduces solar heat gain and urban heat island effects. [Marceau and VanGeem \(2007\)](#) tested a wide range of concrete mixture designs and found all of them were effective in reflecting solar energy and could contribute to the reduction of urban heat islands when used in pavement, roofing, or cladding. White cement mixtures showed the highest reflectivity.

3.2—Blended hydraulic cement

Blended hydraulic cement is a combination of portland cement and other cementitious or mineral constituents, sometimes referred to as composite cements. In the United States, blended cements are manufactured in accordance with ASTM C595/C595M and [C1157/C1157M](#) as well as AASHTO M240, whereas in Canada they are governed by [CAN/CSA-A3001](#). As previously mentioned, other stan-

dards such as **BS EN 197-1:2011** also include a wide range of cement classifications that can include other cementitious materials and mineral constituents. In cement production, there are two distinct steps in the process: 1) pyroprocessing that occurs in the kiln; and 2) grinding and blending of clinker and other constituents after the kiln. The nonclinker components of blended cements are added to the clinker after the kiln, and so do not require pyroprocessing as do the clinker raw materials. Exceptions to this are some natural pozzolans that may require either heating or grinding to prepare them for use in cement.

3.2.1 Environmental impacts and blended cement—

The cement industry has made advancements in reducing overall energy use and environmental impact in portland cement production. Further reductions in the environmental impacts of cement are possible. The use of **ASTM C595/C595M**, **ASTM C1157/C1157M**, **AASHTO M240**, or **CAN/CSA-A3001** blended cements can also help to reduce the carbon footprint of concrete. In these cements, higher amounts of slag cement and pozzolans, collectively known as SCMs, are used. The amount of pyroprocessed materials in cement is therefore reduced, as is the amount of calcined limestone, both of which have the potential to reduce the carbon footprint of cement. Blended cements containing SCMs are delivered to the concrete production facility as a single product as opposed to separately supplied and batched SCMs. Although available in the U.S. market, many concrete producers prefer using different proportions of SCMs with portland cement at the concrete production facility.

Blended cements are commonly believed to have slower strength gain and setting characteristics. In practice, the concrete containing them can be comparable in performance to **ASTM C150/C150M** Type II portland cement, as shown in Fig. 3.2.1. There are advantages to the use of blended cements (as opposed to concretes with SCMs added separately to the concrete mixer) with regard to chemical and physical properties that can be better controlled. However, some concrete producers feel that more flexibility in use of different replacement levels of SCMs is available than with fixed-proportion, blended cements. Ternary concrete mixtures may also be produced using an **ASTM C595/C595M** Type IT blended cement, or by batching three separate cementitious materials, such as cement, fly ash, and silica fume at the concrete batching facility. Ternary blends are another method of achieving environmentally efficient, yet practical, concrete mixtures.

3.2.2 ASTM C595/C595M cement types—**ASTM C595/C595M** is a prescriptive specification that recognizes four main classifications of blended cements: 1) Type IP; 2) Type IS; 3) Type IL; and 4) Type IT. These cements can be produced by blending individual constituents or by intergrinding.

Type IP incorporates portland cement or portland cement clinker and a pozzolan in amounts of up to 40 percent by mass. The pozzolans used can include fly ash, natural pozzolan, or silica fume.

Type IS cement combines portland cement or portland cement clinker with some form of slag cement. Type IS cement can be blended, as is the case with portland cement

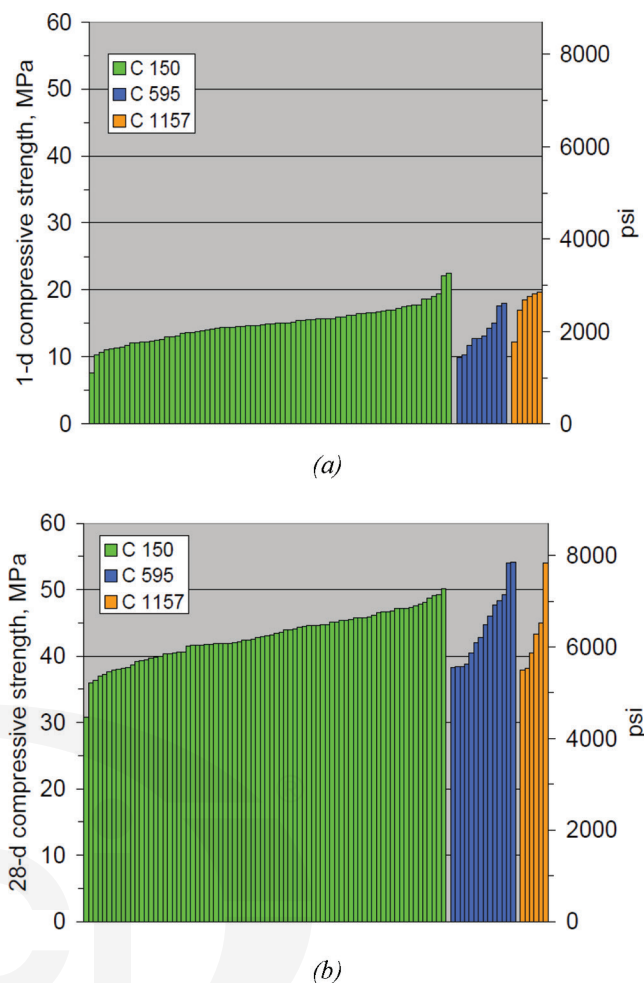


Fig. 3.2.1—(a) One-day; and (b) 28-day strengths of **ASTM C150/C150M** Type II, **ASTM C595/C595M**, and **ASTM C1157/C1157M** cements from a 2004 survey (Bhatty and Tennis 2008). Note that each column represents a single cement sample of the type in the color key.

and slag cement, or interground, as with portland cement clinker and slag cement. The pozzolan or slag content of blended cements can vary depending on the desired characteristics of the final product.

Type IL cement contains uncalcined limestone that is ground to cement fineness. The amount of limestone is limited to 5 to 15 percent by mass of the cement. This will be discussed in more detail in 3.2.5.

Ternary blended cement, Type IT, is a blended cement made with two SCMs or ground limestone and an SCM. The specifications were also revised to provide transparency in communication with regard to the amount and type of SCMs and limestone in blended cements.

3.2.3 Performance-based cements—In the United States, **ASTM C1157/C1157M** is a performance specification for hydraulic cement and provides even greater flexibility in producing cements with lesser environmental impact. Specification requirements are in place to ensure performance of these cements based on testing, rather than indirect (prescriptive) limits. **ASTM C1157/C1157M** are classified based on their potential application. For

example, GU is designated for general use and HE for high-early-strength requirements. Other designations include MS (moderate sulfate resistance), HS (high sulfate resistance), MH (moderate heat of hydration), and LH (low heat of hydration).

3.2.4 Potential reduction of emissions—ASTM C595/C595M and ASTM C1157/C1157M provide opportunities for lessening the environmental impact of concrete.

Tables 3.2.4a and 3.2.4b give estimates of emission reductions based on the amounts of noncalcined limestone or SCMs used in cements, based on the approach of Nisbet (1996) and The Environmental Protection Agency (2014).

3.2.5 Portland-limestone cements (PLCs)—Globally, portland-limestone cements, or PLCs, have been used for many years (Hooton et al. 2007). Limestone is a partial constituent to replace clinker in these cements. The limestone is processed by intergrinding with portland cement clinker or blending ground material. In some cases, it may be added to the concrete mixture (Hooton et al. 2007). As previously noted, **ASTM C150/C150M** now allows up to 5 percent limestone as a constituent in portland cement. ASTM C595/C595M Type IL PLCs are cements that use percentages of 5 to 15 percent limestone replacement; these are not covered by ASTM C150/C150M.

Limestone is easier to grind than clinker, requiring less energy to prepare the raw material (Cost 2008). Cement with limestone can also increase concrete strength and reduce porosity, thereby increasing durability (Matschei et al. 2007b). Calcination of the limestone is not necessary, thereby avoiding some CO₂ emissions. The CSA A3000 (Hooton et al. 2007) allows up to 15 percent limestone in portland-limestone cements. In Canada, PLC use is governed by CSA A23.1/A23.2 and NBC 2015. Prior to this in North America, PLC use had been minimal due to limited adoption of industry standards. ASTM C1157/C1157M cements with approximately 10 percent limestone have been produced at several locations in the United States since the mid-2000s.

An approach in Canada to the introduction of PLC has been to produce PLC with equivalent performance to portland cement manufactured from the same clinker relative to strength gain and setting characteristics. The equivalent performance is achieved by grinding the PLC to a higher fineness, the increase typically being approximately 100 to 120 m²/kg for PLC with 12 percent limestone. Laboratory and field testing of full industrial trial grinds were conducted in Canada prior to the inclusion of PLC in the Canadian Standards (Thomas and Hooton 2010). The testing included strength development and durability on a wide range of concrete mixtures with and without SCMs and confirmed that PLC with up to 15 percent interground limestone can be produced with equivalent performance to portland cement. In one paving trial, PLC was used with 50 percent SCM—combined fly ash and slag; the cementitious materials component of this concrete consisted of just 41.5 percent portland cement clinker (Thomas et al. 2010a). In another trial, a blended PLC was produced by intergrinding 12 percent limestone and 15 percent slag together with clinker and gypsum,

Table 3.2.4a—Estimated kiln emissions savings potential (lb of emissions per ton of cement production [kg per metric ton])*

	5 percent CR [†]	20 percent CR [†]	35 percent CR [†]
SO ₂	0.30 (0.15)	1.16 (0.58)	2.04 (1.02)
NO _x	0.30 (0.15)	1.16 (0.58)	2.04 (1.02)
CO	0.06 (0.03)	0.20 (0.10)	0.36 (0.18)
CO ₂	94.30 (47.15)	377.18 (188.59)	660.42 (330.21)
THC (total hydrocarbons)	0.00 (0.00)	0.02 (0.01)	0.06 (0.03)

*Following the approach of Nisbet (1996) and using The Environmental Protection Agency (2014) emissions factors.

[†]Clinker reduction (CR)—clinker production is the primary source of CO₂ release in cement manufacture; the ability to reduce the amount of clinker per ton in a finished cement may reduce its emissions.

Table 3.2.4b—Estimated kiln emissions savings potential, tons per year (metric tons per year)*

	5 percent CR	20 percent CR	35 percent CR
SO ₂	13,358 (12,300)	54,344 (49,300)	95,240 (86,400)
NO _x	13,358 (12,300)	54,344 (49,300)	95,240 (86,400)
CO	2425 (2200)	9700 (8800)	16,976 (15,400)
CO ₂	4,417,513 (4,007,500)	17,669,940 (16,029,900)	30,939,233 (28,067,600)
THC	331 (300)	1323 (1200)	2315 (2100)

*Using data in Table 3.2.4a and assuming 85 million metric tons (94 million tons) per year per year of portland cement production.

and this blended cement, containing just 68 percent clinker, provided equivalent performance in terms of concrete strength and durability as portland cement produced with 91 percent of the same clinker (Thomas et al. 2010b).

Intergrinding clinker and limestone produces an improved (broadened) particle size distribution compared to a clinker alone, with the softer limestone grinding finer than the harder clinker. In addition to improving particle packing, the fine limestone particles also act as nucleation sites, thereby increasing the rate of hydration of the calcium silicates at early ages and, possibly, improving distribution of hydrates. Clinker particles can also be ground finer compared with portland cement, which will increase the degree of hydration of the PLC at any given age. Furthermore, it has been demonstrated that CaCO₃ will react chemically (although to a small extent, depending on the tricalcium aluminate [C₃A] content of the clinker) with the aluminate phases to form carboaluminate phases (Bonavetti et al. 2001), which may contribute to reducing the porosity and increasing the strength of the paste (Matschei et al. 2007a). Any additional aluminates supplied by pozzolans and slag could increase the formation of carboaluminate.

The only significant concern with the use of PLC as the sole cementing material is increased potential for the thaumasite form of sulfate attack, if poor-quality concrete is exposed to sulfates at temperatures of approximately 50°F (10°C) or lower. It has been found that, when used with appropriate levels of pozzolans or slag cement, PLC does not

exhibit signs of thaumasite form of sulfate attack. (Hooton et al. 2010).

3.2.6 Grinding aids—Traditional grinding aids are organic amino alcohols (such as triethanolamine [TEOA] or triisopropanolamine [TIPA]) or glycol materials added at low dosages ranging from 0.02 to 0.05 percent to affect the process of dry grinding of most solid materials, reducing overall grinding energy. Examples include all types of portland cement, slag cement, clay cement, and chalk. Grinding aids adsorb onto the existing and newly created cement particle surfaces, partially neutralizing the charges present on the surface particles that develop during milling. This reduces the surface-free energy of the material being ground and enhances separating capabilities that will lead to increased production volume. Improved or higher cement production rates lead to lower specific energy consumption per unit of cement, reducing one of the most electricity-consuming processes in cement production (60 to 70 percent of the total electricity consumed in a cement plant). Use of grinding aids also helps improve the flowability of cement. New performance-enhancing grinding aids such as polycarboxylate polymers, in addition to the traditional grinding aid function, are used to modify setting or strength properties of concrete. These grinding aids also have shown enhanced particle dispersion and the ability to increase cement fineness capabilities. Increasing fineness in blended cements allows for higher clinker replacements with SCMs or limestone, reducing the CO₂ emissions in concrete.

3.3—Supplementary cementitious materials

Supplementary cementitious materials (SCMs) are a class of materials that can be used to replace part of the portland cement in concrete. Their application varies and could depend on the type of SCM. In addition to replacing a portion of the portland cement in a particular mixture proportion, they may be added to the total cementitious content in some cases. When properly proportioned, the use of SCMs can help achieve desired concrete properties for the anticipated use and exposure of the concrete. Though SCMs can be incorporated in blended cements, they can also be added separately by a concrete producer at their batch plant or production facility.

Many SCMs are by-products of industrial processes and their use removes them from the waste stream. These include fly ash, slag cement, silica fume, and rice husk ash. Other SCMs, such as diatomaceous earth, volcanic ash, or expanded shale, are classified as natural pozzolans. Some natural pozzolans require processing prior to use in concrete, which may affect the degree to which they may reduce the embodied environmental impact of the concrete. Depending on the type of natural pozzolan, the processing may include grinding or, in some cases, thermal treatment. SCMs can enhance the performance and durability of concrete. The particular SCM or the proportion of SCM used may be varied to help provide enhanced performance over a range of exposures and applications of concrete.

The judicious inclusion of SCMs in concrete can reduce the amount of portland cement used per unit volume of concrete,

Table 3.3a—Embodied energy and embodied carbon of various binder components (Circular Ecology Ltd. 2011)

Component	Embodied energy, MJ/kg	Embodied carbon, kg CO ₂ /kg
Cement	4.5	0.73
Fly ash	0.10	0.008
Slag cement	1.60	0.083
Ground limestone	0.62	0.032

Table 3.3b—Embodied energy and embodied carbon of various BS 8500-1:2015/40 MPa concrete (general structural) mixtures (Circular Ecology Ltd. 2011)

Binder	Embodied energy, MJ/kg	Embodied carbon, kg CO ₂ /kg
100 percent cement	1.03	0.163
85 percent cement, 15 percent fly ash	0.97	0.152
70 percent cement, 30 percent fly ash	0.89	0.136
75 percent cement, 25 percent slag cement	0.91	0.133
50 percent cement, 50 percent slag cement	0.78	0.100

and thus some of its environmental impact. Additionally, this may reduce both the rate of virgin resource use for cement production and disposal of industrial by-products.

The environmental footprint of concrete is sensitive to the binder composition (3.4). The relative embodied energy and embodied carbon of different binder components can vary widely (Circular Ecology Ltd. 2011) (Table 3.3a). Their relative proportioning then impacts the embodied energy and embodied carbon of concrete (Table 3.3b). These tables are provided for illustrative purposes only. Preference is given to specific quantitative comparisons using appropriate data.

Based on the included content, Tables 3.3a and 3.3b should appear after each of fly ash, slag, and limestone have been mentioned.

Cement, slag cement, and fly ash all have European-related organizations coordinating efforts to improve their respective organization's contribution to further sustainable construction. In addition to the organizations for slag and fly ash, a silica fume organization was organized and formally announced in early 2013. Similarly, in the United States there is the Slag Cement Association (SCA), the American Coal Ash Association (ACAA), and the Silica Fume Association (SFA).

3.3.1 Coal fly ash—Coal fly ash is an important pozzolan because it is widely used in concrete. Fly ash is the mineral residue from the combustion of coal, typically in the generation of electricity at a power plant. The physical and chemical properties of this type of fly ash can vary considerably from power plant to power plant, due to the different sources of coal used, as well as different combustion and emission control systems. Coal fly ash performance can be influenced

by its chemical and physical makeup. Standards in some countries, such as CAN/CSA, classify the type of coal fly ash by its calcium content, reported as CaO. In the United States, fly ash is classified according to [ASTM C618](#) as either Class C (pozzolanic and cementitious) or Class F (pozzolanic) based on the sum of the oxides of silica, alumina, and iron (SiO_2 , Al_2O_3 , and Fe_2O_3).

The performance of a particular coal fly ash in concrete can depend on a number of factors, including the combination of materials in the concrete mixture, the proportion of the ash, and the characteristics of the ash. That said, properly proportioned concrete mixtures containing fly ash can enhance the strength and durability of concrete, potentially extending the service life, and therefore the sustainability, of the structure.

Coal fly ash can enhance the performance of concrete when compared to concrete manufactured with portland cement only. Long-term compressive strength may improve, and some ashes are very effective in helping to reduce the effects of alkali-silica reaction and sulfate attack ([Thomas 2009](#)). In mass concrete applications such as mat foundations, heat generated during the concrete's hydration can cause heat gradients in the concrete that can lead to unacceptable thermal cracking due to internal or external restraint. Controlling the early heat of hydration is critical, and properly designed and proportioned mixtures can help to offset this. This may necessitate the use of higher-volume fly ash mixtures. The development of high-volume fly ash concrete mixture proportions is typically attributed to [Malhotra \(1999\)](#), who developed mixtures with over 60 percent cement replacement by fly ash. As with all mixtures with high volumes of SCMs, attention should be paid to the concrete curing conditions to achieve the desired properties. Prolonged wet curing or higher curing temperatures may be required, depending on the mixture proportions. Further curing information can be found in [ACI 232.3R](#).

When used at high replacement levels, when placed at cold temperatures, or both, the relatively slower rate of strength development of fly ash concrete is a disadvantage in applications where high early strength is required. In some applications, however, the concrete may not be loaded to its design value until months after its placement, and it may be acceptable to specify 56- or 90-day strengths instead of the conventional 28-day strengths, provided that the concrete will receive sufficient curing. If normal strength development is critical, accelerators are available to speed up the hydration rates of fly ash concrete mixtures ([Shi and Day 1995](#); [Shi 1998](#)).

Coal fly ash may present some challenges for the concrete producer. Color may vary due to fluctuations in chemistry. Unburned carbon content can affect the ability to entrain air in concrete. The amount of the unburned carbon and its potential impact on the effectiveness of the air-entraining admixture can be monitored by the concrete producer and mixtures adjusted to attain the desired result.

The coal fly ash industry is working to improve quality control and has developed technologies to help reduce the amount or offset the effects of the carbon content of fly ash. Other research to assess the surface area and amount of

carbon and methods to address its impact on concrete has also been performed ([Ley et al. 2008](#); [Kulaots et al. 2003](#); [Freeman et al. 1997](#)).

Fly ash, as a by-product of coal combustion, would require disposal if not used beneficially. This shortens the useful life of landfills and wastes a valuable material. Although widely available, the use rates of generated fly ash vary widely within the United States and internationally. Usage rates range from as low as 3.5 percent in India to as high as 93.7 percent in Hong Kong ([Malhotra 2000](#)). Although beneficial as an SCM, there are technical reasons that a particular fly ash may fall outside of specification limits, making it unsuitable for concrete use and, therefore, affecting use potential and rates. According to the [American Coal Ash Association \(2011\)](#), U.S. fly ash generation was 59.9 million tons (54.3 million metric tons), of which 11.7 million tons (10.6 million metric tons) were used directly in concrete, concrete products, or grout. Based on the previously stated carbon intensity factor of 0.88 units of CO_2 per unit of cement and assuming a 1-to-1 replacement rate (fly ash to cement), it could be estimated that the use of coal fly ash in those applications avoided approximately 10.3 million tons (9.3 million metric tons) of CO_2 emissions in 2011. An additional 2 million tons (1.8 million metric tonnes) of fly ash was used as a component of blended cement, or as in raw feed for cement clinker production.

The use of coal fly ash as an SCM provides benefits related to sustainable concrete in enhancing concrete performance, reducing the amount of material in the waste stream, and helping lower the environmental footprint of concrete.

3.3.2 Slag cement—Slag cement is a by-product of the steel industry, derived from granulated blast-furnace slag. Granulated blast-furnace slag is the glassy granular material formed when molten blast-furnace slag is rapidly chilled, as by immersion in water. This material is then ground to produce slag cement. The first recorded production of blended portland blast-furnace slag cement was in Germany in 1892, and since the 1950s, use of slag cement as a separate cementitious material has become widespread in many different countries ([ACI 233R](#)).

Molten slag is handled in various ways at a steel mill. If the molten slag is allowed to cool slowly, it crystallizes into a solid mass. This air-cooled slag may then be crushed and sized and sometimes used as an aggregate. In producing slag cement, the molten slag is rapidly cooled after leaving the furnace in a process called granulation. This essentially stops the crystallization process and produces the glassy slag granules that can be ground into slag cement. It is only the rapidly cooled granulated slag that has a high cementitious potential.

Because the calcium-to-silicate ratio of the calcium-silicate-hydrate (C-S-H) formed from slag cement is lower than that formed from portland cement, slag cement is able to chemically bind a larger amount of alkali in the C-S-H. The optimum cement replacement level varies depending on application. Percentages from 20 to 50 percent have historically been used in concrete and sometimes in mass concrete as high as 80 percent. As previously mentioned, the concrete industry has also seen an increase in the use of ternary