Report on the Role of Materials in Sustainable Concrete Construction

Reported by ACI Committee 130
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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.

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

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Reported by ACI Committee 130

Julie K. Buffenbarger, Chair
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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, chemical 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 (CO$_2$) emissions. CO$_2$ 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 (CaCO$_3$) to calcium oxide (CaO), releasing CO$_2$ in the process. Approximately 40 percent of the CO$_2$ 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 CO$_2$ per unit of cement (PCA 2016). The percentage of total annual CO$_2$ from cement production can fluctuate based on total CO$_2$ emitted and cement production levels. In 2010, the U.S. Environmental Protection Agency (EPA) (2012) data showed the portion of total CO$_2$ 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 CO$_2$ released globally (Le Quéré et al. 2016).

Although CO$_2$ makes up a significant portion in GHG emissions, other compounds such as methane (CH$_4$) and nitrous oxide (N$_2$O) are also considered in assessing environmental impacts of a material. The combined impact of GHG emissions is commonly referred to as CO$_2$ equivalents, or CO$_2$e. CO$_2$e is a measurement used to normalize the emissions from various greenhouse gases based on their global warming potential (GWP). CO$_2$e are commonly expressed as terragrams of carbon dioxide equivalents (a terragram is 1 million metric tons). The CO$_2$e for a gas is derived by multiplying the tons of the gas by its associated GWP, thus: TgCO$_2$e = (Gg of gas) × (GWP) × (Tg/1000Gg). (Environmental Protection Agency 2012). For example, the GWP of CH$_4$ is 24; that is, the impact of unit mass of CH$_4$ may have a similar impact on global warming over 100 years as 24 units mass of CO$_2$.

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 mechanical processing (grinding/blending) cement formulations, and the inclu-
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/precalcer 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 in cement manufacturing—Cement manufacturing uses some
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 covered in CAN/CSA-A3001. As previously mentioned, other stan-
There are advantages to the use of blended cement 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 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 mixes 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 mixes.

### 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 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 cements 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 hydra-

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 reduc-
tions 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 lime-
stone 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 C95/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 port-
land 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
cementitious materials 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 lime-
stone and 15 percent slag together with clinker and gypsum,
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 hydra-
ation 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 aluminat-
e [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 thau-
masite 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

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

<table>
<thead>
<tr>
<th>Component</th>
<th>5 percent CR</th>
<th>20 percent CR</th>
<th>35 percent CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>0.30 (0.15)</td>
<td>1.16 (0.58)</td>
<td>2.04 (1.02)</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.30 (0.15)</td>
<td>1.16 (0.58)</td>
<td>2.04 (1.02)</td>
</tr>
<tr>
<td>CO</td>
<td>0.06 (0.03)</td>
<td>0.20 (0.10)</td>
<td>0.36 (0.18)</td>
</tr>
<tr>
<td>CO₂</td>
<td>94.30 (47.15)</td>
<td>377.18 (188.59)</td>
<td>660.42 (330.21)</td>
</tr>
<tr>
<td>THC (total hydrocarbons)</td>
<td>0.00 (0.00)</td>
<td>0.02 (0.01)</td>
<td>0.06 (0.03)</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th>Component</th>
<th>5 percent CR</th>
<th>20 percent CR</th>
<th>35 percent CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>13,358 (12,300)</td>
<td>54,344 (49,300)</td>
<td>95,240 (86,400)</td>
</tr>
<tr>
<td>NOₓ</td>
<td>13,358 (12,300)</td>
<td>54,344 (49,300)</td>
<td>95,240 (86,400)</td>
</tr>
<tr>
<td>CO</td>
<td>2425 (2200)</td>
<td>9700 (8800)</td>
<td>16,976 (15,400)</td>
</tr>
<tr>
<td>CO₂</td>
<td>4,417,513 (4,007,500)</td>
<td>17,669,940 (16,029,900)</td>
<td>30,939,233 (28,067,600)</td>
</tr>
<tr>
<td>THC</td>
<td>331 (300)</td>
<td>1323 (1200)</td>
<td>2315 (2100)</td>
</tr>
</tbody>
</table>

*Using data in Table 3.2.4a and assuming 85 million metric tons (94 million tons) per year per year of portland cement production.
3.2.6 Grinding aids—Traditional grinding aids are organic amino alcohols (such as triethanolamine [TEOA] or trisopropylamine [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 CO$_2$ 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, 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

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

<table>
<thead>
<tr>
<th>Component</th>
<th>Embodied energy, MJ/kg</th>
<th>Embodied carbon, kg CO$_2$/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>4.5</td>
<td>0.73</td>
</tr>
<tr>
<td>Fly ash</td>
<td>0.10</td>
<td>0.008</td>
</tr>
<tr>
<td>Slag cement</td>
<td>1.60</td>
<td>0.083</td>
</tr>
<tr>
<td>Ground limestone</td>
<td>0.62</td>
<td>0.032</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Binder</th>
<th>Embodied energy, MJ/kg</th>
<th>Embodied carbon, kg CO$_2$/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 percent cement</td>
<td>1.03</td>
<td>0.163</td>
</tr>
<tr>
<td>85 percent cement, 15 percent fly ash</td>
<td>0.97</td>
<td>0.152</td>
</tr>
<tr>
<td>70 percent cement, 30 percent fly ash</td>
<td>0.89</td>
<td>0.136</td>
</tr>
<tr>
<td>75 percent cement, 25 percent slag cement</td>
<td>0.91</td>
<td>0.133</td>
</tr>
<tr>
<td>50 percent cement, 50 percent slag cement</td>
<td>0.78</td>
<td>0.100</td>
</tr>
</tbody>
</table>
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 (SiO₂, Al₂O₃, and Fe₂O₃).

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- to 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 CO₂ 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 CO₂ 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...
cementitious systems—that is, a blend of ordinary portland cement, fly ash or other pozzolans, and slag cement. ASTM C595/C595M recognizes such systems for blended cement (Type IT), and concrete producers can also add the materials separately at the batch plant or production facility. Slag cement may be a constituent of these cements or systems.

The use of slag cement as an SCM also provides benefits related to sustainable concrete in enhancing concrete performance, reducing the amount of material in the waste stream, and helping lower the carbon footprint of concrete. Like other SCMs, when properly proportioned and cured, slag cement improves many mechanical and durability properties of concrete and can generate less heat of hydration.

3.3.3 Silica fume—Condensed silica fume is a by-product of the silicon metal and ferrosilicon alloy industry and is another example of beneficial use of an industrial by-product. This siliceous material improves both strength and durability of concrete to such an extent that high-performance concrete mixture proportions often call for the addition of silica fume. Although it is typically used in modest amounts (approximately 5 to 8 percent by mass) and sometimes as an addition to the cementitious material rather than a replacement, the potential to extend structural service life, optimize strength and element sizing, and the fact that it is a recovered material, fits well in sustainable building. Silica fume acts both as a reactant as well as improving packing of the binder particles. Its use is found in ACI 234R and ASTM C1240.

3.3.4 Other pozzolans—There are many different pozzolans, most notably those considered natural ones. Among these are metakaolin, expanded shale, expanded slate, expanded clay, pumice, rice husk ash, volcanic ashes, and materials such as diatomaceous earth. These materials may require some form of processing before use in concrete. This may entail thermal processing as in the case of metakaolin, or physical grinding in the case of mined pozzolans such as diatomaceous earth. Such processing would add to, and need to be accounted for when assessing, the environmental impact of such materials. As with other SCMs, these pozzolans can be used in concrete to replace part of the Portland cement, to enhance performance characteristics and potentially extend service life. More information on natural pozzolans is found in ACI 232.1R. They are specified in ASTM C618 as Class N pozzolans.

3.3.5 Other materials—Along with historically used SCMs, there has been research on the potential use of other materials as SCMs. These materials fall outside the ASTM definition of SCMs, such as slag cement, fly ash, or silica fume. Many materials may possess chemical or mineralogical properties that might be considered for use in concrete. Wood ash and various types of nonferrous slags are just a few examples of these types of materials. Also, finely ground glass powder derived from recycled glass has been shown to be an effective pozzolan (Tagnit-Hamou and Bengougam 2012; Jin 1998; Byars et al. 2004; Shao et al. 2000). Many of these materials deserve closer attention because their use as SCMs may be of benefit in concrete rather than being sent to disposal. Refer to ASTM C1709 and CSA A3004-E1 for guidance on the evaluation of the performance characteristics of these materials.

3.3.5.1 Photocatalytic materials—A relatively novel tool in the effort to combat air pollution is the use of photocatalytic materials (Van Hampton 2007). These chemicals, most notably titanium dioxide (TiO₂) particles, can be mixed with cement or added as a separate ingredient in concrete to give concrete an inherent ability to convert pollutants such as carbon monoxide to carbon dioxide, NO₂ to nitrate, SO₃ to sulfate, and oxidizing some organics when exposed to sunlight or other ultraviolet light sources. The process is somewhat analogous to photosynthesis. Because the photocatalytic materials are catalysts, they are not consumed in the reactions and will continue to work at reducing pollution.

These agents also help maintain the light-colored appearance of concretes that are referred to as self-cleaning. The breakdown of organic materials decreases staining of the concrete, which reduces maintenance, while maintaining its reflectance in supporting heat island mitigation.

3.4—Non-portland cement binders

3.4.1 Concrete without portland cement—This section provides an overview of concretes in which the binder phase contains no portland cement. The non-portland cement binders discussed herein are alkali-activated slag cement, alkali-activated fly ash, calcium aluminate cements, and calcium sulfoaluminate cements. Note that most of these binder systems have been used for specific applications across the world for several decades. Recent concerns about the environment, however, have created a renewed interest in these lower-energy and CO₂-intensive binder systems. Although the materials discussed in the following are considered the most industrially viable alternatives to Portland cement, this document does not claim to provide a comprehensive list of all possible non-portland-cement binder materials.

3.4.2 Alkali-activated slag and alkali-activated fly ash concretes—Slag cement is produced by finely grinding the glassy granular material formed when molten blast-furnace slag is rapidly chilled. As slag cement is a recovered material from the iron industry, its intrinsic embodied energy is low. An alkali-activated slag (AAS) concrete is one in which the binder phase is made of slag cement, water, and an alkali activator that triggers the chemical reactions involving dissolution of slag and precipitation of calcium silicate and calcium aluminosilicate phases that serve as the binder phase of concrete. These systems contain no Portland cement. Although slag is cementitious and can self-activate, the reaction is typically slow and requires external alkali activators to enhance reaction rates and form stronger products. Sufficient alkali content is also necessary for the development of significant strength. Because slag is deficient in alkalis, these have to be supplied externally. These AAS also appear in the literature with a variety of names such as alkali-activated cements (Palomo and López dela Fuente 2003) and alkali-slag cements (Roy 1999).

Alkali-activated fly ash is another potential substitute for Portland cement. Fly ash is a coal combustion by-product...
and is primarily composed of aluminosilicate glass, which is formed due to rapid cooling from the molten state within the flux gas of a coal power plant. The alumina (Al₂O₃) and silica (SiO₂) phases originate from clay impurities that are intermixed with coal during the natural process of coal formation. Similar to slag, fly ash (ASTM C618 Class C and Class F) can be activated by an alkaline solution to promote dissolution of fly ash and formation of a binder phase. Additional heat curing may be needed to ensure desirable early-age strength and property development in alkali-activated fly ash concrete.

Some commonly used alkaline activating agents are sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃, also known as water glass) or combinations of these (Shi and Day 1996; Krizan and Zivanovic 2002). A variety of industrial by-products containing alkalis and sulfates such as cement kiln dusts are also equally effective in activating slag (Chaunsali and Peethamparan 2011). Among the activators used, water glass is widely reported to give rise to rapid hardening and high compressive strengths (Oh et al. 2010). Note that some of these activators are very corrosive alkaline liquids that require safety precautions during manufacture of the concrete.

The main hydration product in an AAS systems is C-S-H, with a low Ca/Si ratio regardless of the type of activator used (Song et al. 2000; Wang et al. 1994; Richardson and Cabrera 2000; Davidovits 2008). In addition, an Al-modified C-S-H is also present due to the alumina content of slag. The morphology of the hydration products changes with the activator and other hydration conditions (Wang and Scrivener 1995; Richardson et al. 1994; Ravikumar et al. 2010). In alkali-activated Class F fly ash, the primary binder phase is an alkali-alumino-silicate-hydrate (N-A-S-H) phase, also known as geopolymer (Davidovits 1991). This geopolymer phase, which has compositional similarities with natural zeolites, serves as concrete binder. In addition to Class F fly ash, geopolymers can be produced using metakaolin or other aluminosilicate materials. Class C ash is compositionally in between Class F ash and slag, as it contains significant quantities of lime, silica, and alumina (Duxson 2009). As a result of alkali activation, Class C fly ash primarily forms an Al-modified C-S-H gel, which is also known as C-A-S-H gel.

Alkali-activated concretes exhibit useful strength (Atis et al. 2009), durability against chemical/acid attack, chloride penetration (Fernández-Jiménez and Puertas 2002; Puertas et al. 2009), and a variety of other potentially valuable characteristics such as fire and wastewater resistance. A wide range of different alkali-activated binder systems are available and discussed in the literature. The performance with respect to rheology, strength development, shrinkage, and durability performance varies widely. The performance of each product and the systems in place to ensure consistency and safety need to be carefully assessed before use.

An advantage of alkali-activated concretes is that they have a low CO₂ emission rate embodied energy compared to traditional portland cement concretes. This is because these systems do not require calcination and the energy-intensive, high-temperature clinkerization processes involved during production of portland cement.

There will be embodied energy in the activator system. For example, the energy to produce sodium hydroxide is 20.5 MJ/kg (Hardjito and Rangan 2005) compared with 5.35 MJ/kg for portland cement (Goggins et al. 2010). As activators are used at approximately 10 percent mass of solid binder, the reduction in embodied energy for the binder system could be approximately 60 percent.

When specifying non-portland-cement binders, users need to consider and validate all performance characteristics, such as workability, durability, and fire resistance of these portland cement substitutes to ensure they are suitable for the intended purpose (ASTM C1709).

3.4.3 Calcium aluminate cements—Calcium aluminate cements (CACs) are a special class of cement containing primarily aluminates and calcium. Small amounts of ferrite and silica are also typically present. CACs were invented in the early 1900s to resist sulfate attack. CACs are inherently rapid-hardening and can be rapid-setting and adjustable with appropriate chemical admixtures. These cements are often used in refractory applications; self-leveling floor compounds; as a component in grouts, mortars, bonding agents and other adhesives; highly-abrasion-resistant applications; rapid repair; rehabilitation and construction of concrete flatwork such as sidewalks and overlays; and full-depth pavement construction. The rapid-hardening properties; resistance to sulfate attack, acid attack, and alkali-aggregate reaction; and abrasion resistance make these cements desirable in a wide range of special applications (Scrivener and Capmas 1998). As there is no calcination of limestone, the manufacturing process of CACs generates significantly less CO₂ than portland cement—roughly on the order of 50 percent less (Gartner 2004; Juenger et al. 2011). However, there is slightly more grinding energy required (than portland cement) due to the increased strength of the clinker (Juenger et al. 2011; Scrivener and Capmas 1998).

The most widely discussed and controversial aspect of CACs is the process referred to as conversion. Conversion is a process where metastable hydrates (CAH₁₀ and C₂AH₆) formed at low and moderate temperatures (41 to approximately 158°F [5 to approximately 70°C]) convert to stable hydrates (C₃AH₆) formed at high temperatures (greater than 158°F [70°C]). This process leads to an increase in porosity and subsequent decrease in strength. Conversion is an inevitable process and must be accounted for when designing the concrete mixture. The hydration process of CACs is thus highly temperature-dependent and the time spent during hydration within specific temperature ranges will dictate the type and amount of metastable or stable hydrates, or both, that are formed (Scrivener and Capmas 1998). Several building collapses in the 1970s were attributed to CAC conversion, and many structural codes subsequently banned its use. Since then, research has provided a greater understanding of CAC chemistry and behavior. Furthermore, a report by The Concrete Society (1997) revisited these landmark collapses and revealed that improper structural detailing, a lack of understanding about CAC properties, and not following manufacturers’ guidance had led to most of the structural failures. Improved guidance for predicting long-term prop-
erties and a better scientific understanding of the material have seen resurgence in interest and use of this alternative cementitious binder (The Concrete Society 1997; Juenger et al. 2011). There are several recommendations that have been employed to keep the strength lost during conversion to a minimum. This includes keeping the water-cementitious material ratio (w/cm) below 0.40 and including a minimum cement content of 675 lb/yd³ (400 kg/m³). More information on CACs can be found in Juenger et al. (2011), Scrivener and Capmas (1998), The Concrete Society (1997), Fentiman et al. (2008), and Gosselin et al. (2010).

3.4.4 Calcium sulfoaluminate cements—Calcium sulfoaluminate (CSA) cements are receiving increasing examination from the cement industry and researchers as a lower-energy, lower-CO₂ alternative to portland cement. Such cements are not new; they contain as a primary phase Ye’elimite, Ca₄Al₆SO₁₆, or C₄A₃S in cement chemistry notation, sometimes called Klein’s compound because it was used by Alexander Klein in the 1960s as an expansive additive to portland cement (Klein 1966). China has been industrially producing these cements since the 1970s and their annual production may exceed 1 million tons (907,000 metric tons) (Glasser and Zhang 2001). CSA cements are used for some structural applications, but they are especially well-suited for the precast and cold-weather applications that take advantage of the rapid strength gain of these materials (Su et al. 1997). Their mechanical properties and durability are reported to rival portland cement (Quillin 2001), but much work is needed to fully understand the long-term material performance.

CSA cements lack standardized composition or performance criteria. They are distinguished by the presence of C₄A₃S as the primary cementing phase, belite (C₂S) as a secondary phase, and the absence of alite (C₃S). Other phases that are commonly present include C₃A(S), CA, and C₅S, and gypsum is added for hydration control as in portland cement. Because ettringite is the primary reaction product of C₄A₃S with gypsum and water, these cements can exhibit rapid setting, rapid strength gains, and expansion. These properties, however, can be controlled through manipulating the composition of the cement and through the addition of chemical retarders. Mechanical properties and dimensional stability similar to portland cement can be achieved (Juenger and Chen 2011).

The reputation of CSA cements as environmentally friendly comes from reductions in energy use and CO₂ emissions during manufacturing. CSA clinkers can be made at lower kiln temperatures than portland cement clinkers (2280°F [1250°C] instead of 2460 to 2640°F [1350 to 1450°C]), and are more porous and friable, thereby requiring less energy for grinding (Mehta 1980; Glasser and Zhang 2001). The lime (CaO) content of C₄A₃S is low (36.7 wt. percent) compared to that of C₃S (73.7 wt. percent); therefore, much less limestone is calcined in the production of CSA cements, leading to lower CO₂ emissions. CSA cements may be able to reduce limestone use by 40 percent and energy by 25 percent compared to portland cement (Sharp et al. 1999). One of the primary challenges facing the widespread adoption of CSA cements, aside from further knowledge of its material properties, is the cost of raw materials. The high alumina content demands the use of bauxite as a raw material, which is not widely available and is expensive. Alternatively, the high sulfur and iron contents, when C₃A(S) is included, allow for the use of many types of industrial by-products as raw materials, reducing the cost of the clinker, both in terms of the economy and the environment (Palou and Majling 1995; Phair 2006).

3.4.5 Recycled glass-based cements and concretes—One incentive behind using recycled soda-lime glass, such as bottles and windows in concrete, is the prohibitive costs of shipping recycled glass from collection points to remelting facilities that manufacture new glass products. Another incentive is use of glass powder as a pozzolanic material, given that access to a quality pozzolan may be limited in some locations. As of 2003 in the United States, approximately 600,000 tons/year (544,000 metric tons/year) of recycled glass is landfilled or stockpiled in hopes that future technologies would allow a profitable use of this material (Reindl 2003). Pulverized glass can be used in concrete as fine aggregates or as cement replacement. Aggregate applications are more developed and have been commercialized in the United States, United Kingdom, and Australia. Desirable strength and workability of concretes containing glass sand have been achieved by proper mixture proportioning (Polley et al. 1998). The main challenge of the use of these materials is the alkali-silica reaction (ASR) of glass particles leading to cracking and deterioration of concrete. ASR, however, has been successfully controlled by:

a) Use of fly ash or other suitable SCMs (Shafatian et al. 2013)

b) Use of glass aggregates finer than No. 50 (0.3 mm) sieve (Jin et al. 2000)

c) Annealing crushed glass before use in concrete (Rajabi-pour et al. 2010; Maraghechi et al. 2012)

Lithium admixtures and use of glass powder as a cement supplement may also be effective in mitigating ASR in these materials (Shayan and Xu 2006).

In comparison, the use of glass powder as a cementitious/ pozzolanic material has not been sufficiently developed despite its promise as a pozzolan with reliable compositional consistency. Due to a high concentration of amorphous silica (approximately 70 percent wt.) soda-lime glass can react pozzolantically with portlandite in a glass-portland cement system and produce low Ca/Si C–S–H. At moderate (up to 30 percent wt.) replacement levels of ordinary portland cement, glass powder has been found to improve compressive strength beyond 28 days; however, early strengths can be reduced when using the same w/cm (Shao et al. 2000; Shi et al. 2005). Fineness of glass powder has a significant impact on its reactivity; glass finer than 38 μm satisfies the strength activity index of ASTM C618 (greater than 75 percent at 7 days) (Shao et al. 2000). By further increasing glass fineness, heat curing, or both, concretes with 3-day strengths surpassing that of PC concrete can be prepared (Shi et al. 2005).

3.4.6 Hydraulic fly ash cements (HFACs)—These cements use high-calcium fly ash (HCFA) along with a functional
additive. This approach produces performance characteristics in concrete similar to portland and other hydraulic cements in terms of strength, durability, and rate of curing or of hydration (Hicks 2010). Depending on the mixture proportion, HFAC materials will meet or exceed the performance specifications contained in ASTM C1157/C1157M. These cements can be used to produce concretes, grouts, mortars, flowable fills, and other specialty mixture proportions. The functional additive consists of some combination of activator and setting retardant (SR). The activator/retardant enhances the hydraulic activity of the calcium aluminosilicates contained in HCFA while the SR helps to control the rate of reaction.

The activator/SR additive is near neutral pH while fresh activated HFAC mixture is slightly more basic (pH of 7 to 9). This is lower than in an OPC mixture. The main reaction products are calcium aluminosilicate hydrates. The set time and strength development of HFCA concrete can be adjusted by changing the concentration of SR. By controlling setting time, these cements can meet ASTM C1600/C1600M standards. These cements are commercialized and have been used in numerous projects (Patel and Kinney 2013; Diaz Loya et al. 2013).

CHAPTER 4—AGGREGATES AND FILLERS

4.1—Introduction

Aggregates are a widely used construction material. Concrete pavements, bridges, foundations, dams, utilities, buildings, and other structures would not be possible without aggregates. Aggregates are produced in most regions worldwide because transportation costs often exceed the on-site cost of aggregate production. They are among the least expensive building materials, and even when used in concrete as 75 or 80 percent of the total mixture, aggregates are usually still less expensive than the binder. The production of aggregates may require less energy than cement, and because they occupy the greatest volume in concrete, reduced energy in production may reduce the embodied energy and CO₂ emissions, thereby contributing to sustainability. Calculations should be made to determine conclusively if using a greater percentage of aggregates reduces the embodied energy and GHG emissions, depending on the production and transportation-related emissions and energy of individual components such as cementitious materials and aggregates.

The aggregate type can dramatically change fresh and hardened concrete properties. Aggregates that are well-graded can decrease the quantity of cementitious materials required while allowing the concrete to perform as desired (Graves 2006). The use of larger maximum-size aggregates, when feasible, is effective in reducing cementitious materials and shrinkage. Without durable aggregates, long-lasting, durable concrete is much more difficult to produce. Durability issues with local aggregates can often be mitigated using blended cements, pozzolans, admixtures, or fine lightweight aggregate (LWA), by changing the chemical and physical properties of the mixture, depending on the aggregate properties (Stark 2006; Thomas 2011).

Most of the concrete aggregates are natural or crushed and can consist of many types of minerals (Barksdale 1991). Some aggregates come from natural deposits such as sand and gravel and are used as-mined, after washing, or in some cases, after crushing. With environmental concerns at the forefront, it is becoming more difficult to obtain approval to mine natural aggregates near rivers and waterways where they are indigenous. Depletion of readily accessible sources of natural aggregates has also led to a reduction in their use. Most crushed aggregates come from stone that is quarried and then processed in mechanical crushers. Crushed and nontraditional aggregates including synthetic, lightweight, recycled/reused aggregates, and mineral fillers will likely be used more frequently in the future due to the environmental concern of mining sand and gravel. There has been an increased use of nontraditional aggregates, some of which are otherwise derived from diverted waste materials, and their use strongly contributes to sustainability by reducing the embodied energy and CO₂ emissions and eliminating waste materials as long as similar or improved concrete performance can be achieved.

As shown in Fig. 4.1 (USGS 2011), it is predicted that crushed aggregates will increase in use in relation to natural aggregates in the future of the U.S. concrete industry; this trend will likely occur in many other parts of the world as well. The use of crushed aggregates poses some challenges. Due to their angular shape, workability is generally decreased (Graves 2006). The dust of fracture or microfines of those materials that pass the 75 μm sieve and are produced in the crushing operation often require the use of admixtures to yield concrete with the desired workability (Graves 2006; Fowler and Rached 2011). The use of nontraditional aggregates, which may be angular in shape, also can affect concrete properties such as workability, pumpability, strength, and modulus of elasticity, depending on the aggregate properties. The use of admixtures and mixture design can help overcome or limit these effects (Mindness et al. 2002).

Given that transporting aggregates long distances uses additional energy and produces more CO₂ compared to local aggregates, local aggregates should be used when feasible, including recycled materials to promote sustainability. The impact of materials should be looked at holistically over the life of the structure; an overall reduced environmental impact can be achieved by using materials with a larger embodied energy and CO₂ emissions, if they significantly increase the service life or substantially reduce cementitious material requirements.

4.2—Natural sand and gravel

Historically, natural aggregates have been the most widely used aggregates in the production of concrete; however, the production of natural aggregates is declining and is predicted to continue to do so in relation to crushed aggregates (USGS 2011) (Fig. 4.1). When properly proportioned, both natural sand and gravel are capable of producing high-quality, sustainable concrete (Graves 2006). Natural aggre-
gates often require little or no mechanical crushing when sizing for use in concrete. Producing natural aggregate in many locations, therefore, requires less energy than other types of aggregates.

Because natural aggregates are generally crushed less, they tend to have rounded edges and smoother surface textures, which further lends itself to many sustainable concrete features. For example, smoother surface textures lead to easier concrete consolidation compared with crushed aggregates. Easier consolidation means less water is needed to achieve workability of the concrete. Less water generally means higher strength, improved durability, and usually less drying shrinkage. As strength increases, it may be possible to reduce the ordinary portland cement content while still achieving the required design concrete strength or workability. Reducing the ordinary portland cement content further reduces the overall embodied energy and CO\textsubscript{2} emissions of the concrete. While admixtures such as high-range water-reducing admixtures will also improve workability, they bring emissions and embodied energy costs of their own.

Using natural aggregate for sustainable concrete, however, requires consideration of basic issues during concrete design. For example, the rounded edges and smooth surface texture that have many benefits in fresh concrete also may present issues such as reduced interfacial transition zone bond strength once the concrete hardens. Clay and clay coatings that naturally occur in the aggregate should be minimized to ensure an adequate interfacial transition zone. As for crushed aggregates, properly sizing the aggregate grading to achieve maximum aggregate packing should be considered to further minimize the paste content. This is discussed in detail in ACI 211.1.

Natural aggregate reserves are often located in proximity to rivers, creeks, and streams. Once permitted reserves are exhausted, the mining areas are reclaimed and often returned to ponds, lakes, and wetland vegetation. These wetland areas become home to many species of wildlife and serve as a natural filter to help cleanse runoff water.

4.3—Crushed stone

There are over 10,000 crushed stone mines in the United States, yet only 1 percent are below ground. Most underground aggregate mines are a maximum of only a few hundred feet (meters) deep. Underground operations are becoming more common, especially for limestone mining in the central and eastern parts of the United States, as the advantages of such operations are increasingly recognized by the producers. By operating underground, a variety of problems usually connected with surface mining, such as environmental impacts and community acceptance, are significantly reduced (USGS 2015a,b). Crushed stone has been an increasingly valuable source of aggregates for decades, but the use of crushed fine aggregate has been more limited primarily due to concerns about workability and, in some cases, the difficulty in meeting ASTM C33/C33M specifications with respect to the minus No. 200 content.

Workability, which is affected by sharp, angular shapes generally produced in the crushing process, can be overcome to some extent by the proper use of admixtures, supplementary cementitious materials (SCMs), or both. Crushed stone aggregates have increased aggregate-to-paste bond strength due to the aggregate shape and texture that usually results in higher flexural and compressive strengths. This may permit reduced ordinary portland cement content and a corresponding reduction in the embodied energy and CO\textsubscript{2} emissions.

ASTM C33/C33M, originally developed for natural sand, limits the amount of material passing the No. 200 (75 μm) sieve to minimize the silt and clay often associated with natural sand deposits. Unfortunately, many crushed fine aggregates do not meet the grading requirements. Particularly, the amount of minus No. 200 (75 μm) fines is generally much greater than permitted by ASTM C33/C33M. Washing to remove excess microfines is usually required to meet ASTM C33/C33M, but this practice has both economic and environmental costs. Trial batching should be employed to determine whether the fines in a particular aggregate are deleterious.
Research has shown that the microfines can be successfully used in much larger percentages—as much as 15 percent or more of the total fine aggregate than permitted by ASTM C33/C33M— to produce concrete with excellent strength and durability when the mixtures are properly designed and the microfines do not contain a significant amount of clay (Fowler et al. 2006; Fowler and Rached 2011). Research has also shown that abrasion resistance is generally greater when up to 15 percent microfines are used compared to concrete made with good-quality natural sand (Fowler and Quiroga 2004). The microfines can be considered as part of the total powder content—that is, ordinary portland cement and supplementary cementing materials—and, in some cases, the cement can be reduced by 20 percent or more and still achieve the same or greater strength. Under these conditions, the use of suitable microfines in concrete, instead of being removed from the fine aggregate and wasted, strongly supports sustainability (Juenger et al. 2006). The use of performance specifications should be encouraged to enable the use of higher amounts of microfines than those permitted in ASTM C33/C33M.

Crushed stone quarries can be reclaimed into usable farmland or pasture, or converted into landfills, lakes, and other recreational sites. These reclamation areas support wildlife in many cases to a greater extent than before the mining operations commenced.

### 4.4—Lightweight aggregates

Lightweight aggregate (LWA) has a long history, with the first known use dating back 2000 years to the Classical Roman period from which there are several remaining lightweight concrete structures in the Mediterranean region. The first modern use of high-performance LWA concrete came when lightweight concrete ships (1917 to 1921) were built in which specified compressive strengths of 5000 psi (35 MPa) were obtained with a unit weight of less than 110 lb/ft³ (1760 kg/m³), using rotary-kiln-produced expanded shale and clay LWA. Commercial normal-weight concrete strengths of that time were approximately 2500 psi (17 MPa) (ESCSI 1971). After 80 years of floating in seawater, core samples verified that the lightweight concrete strength was over 8000 psi (55 MPa) and the samples were in good condition (Sturm et al. 2002).

Expanded shale, clay, and slate (ESCS) structural LWAs are produced in manufacturing plants from suitable raw materials. ESCS is made using the pyroprocessing method that includes a rotary kiln in which raw material is fed into a long, slowly rotating, slightly inclined cylinder where it’s fired to approximately 2000°F (1100°C), resulting in approximately 1.34 MBtu/yd³ (1.85 GJ/m³) or 2.16 MBtu/ton (2.07 GJ/ton) of energy consumed. This manufacturing process, which is similar to that of portland cement, produces a uniform, high-quality ceramic aggregate that is structurally strong, stable, and durable, yet also lightweight and insulative (Holm and Ries 2007).

ESCS LWAs contain a uniform distribution system of pores that have a size range of approximately 5 to 300 μm, embodied in a continuous high-strength vitreous phase. Pores close to the surface of some LWA are readily permeable and filled with water within the first few hours to few days of exposure to moisture. Interior pores often fill extremely slowly, with many months of submersion required to approach full water absorption and are essentially non-interconnected; a small fraction remains unfilled after years of immersion (ACI 213R). Commercially, LWA is most commonly prewetted by sprinklers or by vacuum saturation before it is used for internal curing or when the lightweight concrete will be pumped. When crushed, ESCS tends to absorb water more quickly.

The embodied energy to manufacture ESCS includes mining, manufacturing, and transporting the material to the job site or building product manufacturer. The use of ESCS has been a design choice in thousands of existing structures as the cost of the embodied energy is often paid back in a very short period of time due to reduction in material resulting from reduced loads. Reduced dead loads allow for smaller columns, beams, and foundations, resulting in less overall material being used. Lighter concrete improves thermal performance, lower transportation costs, and reduction of labor costs associated with the building elements, especially when these elements are handled by workers, such as with concrete masonry (Friggle and Reeves 2008; Holm et al. 1984).

ESCS structural LWA concrete contributes to sustainability by:

(a) Reducing the concrete unit weight by 25 to 30 percent, leading to a higher strength-to-weight ratios that requires less concrete and, hence, less dead load to be carried by the structure

(b) Greater fire resistance, resulting in thinner sections when used for fireproofing

(c) Internal curing provided by water absorption in the porous LWA, which improves hydration, reduces shrinkage, and reduces cracking; the lower weight resulting from the addition of LWA also contributes to reduced cracking (ESCSI 2007)

### 4.5—Recycled/reused aggregates

There are many recycled and reused materials that have been used for aggregates in concrete. These include recycled concrete, crushed returned concrete aggregate, screenings, blast-furnace slag, crushed glass aggregate, waste plastic aggregate, recycled scrap tire aggregates, and recycled asphalt pavement aggregates.

#### 4.5.1 Recycled concrete

In-service concrete can be removed and recycled as aggregate for concrete. Recycling concrete is a sustainable practice because it redirects the demolished materials, including concrete and reinforcing steel, from landfills to new construction. Recycling concrete contributes to reduced environmental impacts of land disturbance, especially at a time when the numbers of adequate disposal sites are diminishing and the sources of good-quality aggregates are rapidly becoming depleted. In most urban areas in the United States, where there is a high concentration of in-service concrete, the lack of disposal sites can substantially increase disposal costs and environmental costs, including land use and longer transportation
distances. The use of recycled concrete aggregate (RCA) can be economical and sustainable, particularly in metropolitan areas, when there are higher costs of virgin aggregate materials and higher transportation costs to dispose the removed concrete and deliver the virgin aggregate.

Fresh concrete produced with RCA can be batched, mixed, transported, placed, and compacted in the same manner as conventional concrete. However, mixture proportions for structural concrete produced with RCA should be adjusted to account for differences in the physical properties of RCA compared to crushed stone. RCA is produced from construction debris, which makes the possibility of contamination from reinforcing bar, oils, deicing salts, and other building components higher. Contamination can be deleterious to the performance of RCA in concrete. In many European countries, the use of 20 percent RCAs in structural concrete is standard practice (Federal Highway Administration 2004; RILEM 2005).

4.5.2 Crushed returned concrete aggregate—Every year, it is estimated that an average of 5 percent of the estimated 455 million cubic yards (348 cubic meters) of ready mixed concrete produced in the United States (est. 2006) is returned to the concrete plant. A common approach to recycling returned concrete is to first discharge the returned concrete from the concrete truck in an appropriately designated area of the concrete plant. When hardened, the discharged concrete can be subsequently crushed by a crusher, and the crushed concrete aggregate (CCA) can be used as a portion of the aggregate component in new concrete. CCA is prepared from concrete that has never been in service and thus is not contaminated from in-service exposure, as compared to RCA.

In research conducted by the National Ready Mixed Concrete Association, CCA was produced at a ready mixed concrete plant at three strength classes (Obla et al. 2007). The properties of coarse and fine CCA were found to be different than that of virgin aggregates. It was determined that although the use of CCA had impacts on the concrete properties, these could be addressed through mixture design and testing.

The use of returned concrete aggregate strongly contributes to sustainability by diverting an otherwise waste material from landfills. Its use in concrete eliminates the need for producing an equal volume of natural or crushed aggregate, which reduces or eliminates fuel requirements and associated emissions. (Obla et al. 2007; Kim and Bentz 2007).

4.5.3 Screenings—Crushed stone screenings are a fine aggregate by-product from the crushing, screening, and washing of coarse aggregate sizes. These products typically range in size from minus 3/8 or 1/4 in. (9 or 6 mm) and may include fines as small as 2 µm.

These materials are produced in the same processes used to produce the coarse sizes, therefore using the same energy per unit. It is advantageous to find uses for these by-products so that the energy expended for production is not wasted. The use of screenings leads to sustainability because the fine particles are not washed from the aggregate and, therefore, are not wasted.

Research has shown that some of these products having suitable mineralogy, consistent physical properties, and controlled gradation can be successfully used as a fine aggregate or powder component in concrete, resulting in similar or improved concrete properties. Potential benefits may include reduction in cementitious content, improved durability, increased volume of aggregate per unit volume and increased abrasion resistance (Fowler and Rached 2011; Juenger et al. 2006). Concrete using these products as a fine aggregate constituent can be proportioned, mixed, placed, and finished using traditional methods and materials.

4.5.4 Blast-furnace slag—Blast-furnace slag is a nonmetallic material produced in the production of iron. Iron ore, iron scrap, and fluxes such as limestone, dolomite, or both, are charged into a blast furnace along with coke for fuel. The coke is combusted to produce carbon monoxide, which reduces the iron ore to a molten iron product. This molten iron can be cast into iron products but is most often used as a feedstock for steel production. Approximately 20 percent by mass of iron production is slag. The molten slag, which absorbs much of the sulfur from the charge, consists primarily of silicates, aluminosilicates, and calcium-aluminosilicates.

Different forms of slag products are produced depending on the method used to cool the molten slag. These products include air-cooled blast-furnace slag (ACBFS), expanded or foamed blast-furnace slag, pelleted blast-furnace slag, and granulated blast-furnace slag. Air-cooled blast-furnace slag can be crushed and screened in a process similar to crushed stone.

Expanded or foamed blast-furnace slag results if the molten slag is cooled and solidified by adding controlled quantities of water, air, or steam; the process of cooling and solidification can be accelerated, increasing the cellular nature of the slag and producing a lightweight expanded or foamed product. Foamed slag is distinguishable from ACBFS by its relatively high porosity and low bulk density.

Pelletized blast-furnace slag results when the molten slag is cooled and solidified with water and air quenched in a spinning drum; pellets, rather than a solid mass, are produced. By controlling the process, pellets can be made more crystalline, which is beneficial for aggregate use or more vitrified (for example, glassy), which is more desirable in a cementitious application.

Granulated blast-furnace slag is rapidly cooled by large quantities of water to produce a sand-like granule. While most granulated slag is further processed by grinding into a cementitious material commonly known as slag cement (Chapter 3), unground granulated blast-furnace slag can be used as an aggregate material. In Australia, granulated blast-furnace slag has been used as a partial replacement for fine aggregate in the production of portland-cement concrete. Another aggregate application in Australia is the incorporation of 20 percent by volume of granulated slag with 80 percent by volume dense graded ACBFS crushed aggregate base. The granulated slag acts as a binder material in the production of a high-quality bound aggregate base course (Australasian Slag Association Inc 2002). According to the USGS, 69 percent of blast-furnace slag in the United States was air cooled with 49.7 percent of this portion being used in road base applications (USGS 2015c). The proportion of...
ACBFS currently being produced, however, is decreasing relative to granulated and pelletized blast-furnace slag production. The production of expanded blast-furnace slag is no longer favored and is being replaced by the pelletizing procedure.

ACBFS has been used as an aggregate for concrete, concrete masonry, asphalt pavement, and road bases. Many specifying agencies consider ACBFS to be a conventional aggregate, thereby recognizing a by-product of iron production in everyday construction. Pelletized blast-furnace slag has been used as LWA and for cement manufacture. Foamed slag has been used as an LWA for concrete.

4.5.5 Crushed glass aggregate—There are demonstrated sustainable uses of post-consumer glass aggregate for commodity products that divert waste glass into concrete, including concrete masonry block units and paving stones with up to 100 percent glass aggregate. Concrete mixtures with 100 percent glass aggregate and 28-day compressive strengths exceeding 15,000 psi (103.5 MPa) have already been made using standard procedures (Jin et al. 2000; Meyer 1999). More than 12 million tons (10.9 million metric tons) of glass products are discarded in the United States on an annual basis, and almost three-fourths of this waste stream is landfilled at significant cost to the public (EPA 2009). As more beneficial applications are developed, a higher volume of post-consumer glass can be integrated into concrete. There is a wide variety of architectural and decorative concrete applications that could be produced with glass aggregate, including architectural concrete blocks, building façade elements, wall tiles, panels, partitions, stair treads, countertops, and outdoor furnishings.

Crushed glass has special properties that are beneficial for its use as aggregate to produce sustainable concrete. Because of the lack of water absorption and the smooth surfaces of glass aggregate, the flow properties of fresh concrete with glass aggregate are improved compared to fresh concrete with crushed stone. This means that either workability can be improved at given a w/cm, or the w/cm can be reduced to achieve a specified workability, which in turn increases mechanical strength and durability properties. The smooth surfaces of crushed glass have so far not been shown to negatively affect the mechanical properties of concrete. Glass also has high hardness and abrasion resistance, which makes it a suitable aggregate for paving stones, floor tiles, and other applications subject to long-term surface wear. Glass powder has pozzolanic properties when finely ground, so the finest fraction of crushed glass aggregate is excellent as a filler because of its bond to the surrounding matrix. With reduced water requirements and improved long-term properties, crushed glass aggregate can contribute to a more sustainable concrete.

The use of glass as an aggregate for concrete was contemplated decades ago, but alkali-silica reaction (ASR) caused an insurmountable problem (Philips et al. 1972; Johnson 1974). ASR can occur with aggregates that contain reactive amorphous silica. In the presence of moisture, the resulting ASR gel swells and can cause severe concrete cracking. This is a long-term problem that may manifest itself in concrete after years of seemingly satisfactory service. The complexity of this phenomenon makes it difficult to pre-

determine whether a specific aggregate is potentially reactive or not. If soda lime glass, the common material of household and beverage containers, is used as aggregate in concrete, there is reasonable certainty that ASR-induced damage will occur, provided there is sufficient moisture available to drive the reaction.

The recommended methods for mitigating ASR in concrete using glass aggregate alone or in combination are (Jin et al. 2000):

(a) Grind the glass fine enough to pass No. 100 (0.149 mm) mesh

(b) Use pozzolans such as metakaolin as a coating on glass or additive to concrete, fly ash, slag cement, or fine LWA

(c) Apply a protective coating to the glass—for example, zirconium as for alkali-resistant glass fibers

(d) Modify the glass chemistry to make it less reactive

(e) Seal the concrete to prevent moisture ingress

(f) Use a low-alkali cement

Note that ASR is an extremely complex phenomenon. Even small changes in glass chemistry can make large differences in the reactivity. Each concrete product and glass source needs to be evaluated and tested thoroughly to ensure an acceptable quality and durability of the concrete produced with such glass. Also, replacing natural aggregate with glass aggregate has significant repercussions on the mixture design and concrete production technology, particularly if fully automated production processes are used.

4.5.6 Waste plastic aggregate—There has been a tremendous increase in waste plastics, and many uses have been proposed. There has been a moderate level of research conducted on the use of post-consumer plastic aggregate in concrete. Post-consumer plastic aggregate can be used as an alternative LWA source to achieve a more sustainable concrete. A reduction in unit weight of concrete lowers the total dead load within a structure. At the same time, lightweight concrete containing plastic aggregate can have reduced heat loss and improved thermal insulation properties, which can lead to a reduction in energy consumption and costs.

Post-consumer plastic can be derived from numerous products and can consist of different polymers. The most common source that has been studied is shredded polyethylene terephthalate (PET) bottles, which requires minimal processing and therefore less cost to produce. Its use can become cost-effective, especially in urban areas with a large volume of disposed plastic bottles. Experimental concrete has been produced with 100 percent shredded PET aggregate, but with reduced strength and modulus of elasticity mechanical properties. Replacement of less than 50 percent seems to have much less effect on mechanical properties when compared to a control mixture.

Eight different plastics representing those found in municipal solid waste streams and in industrial waste plastics were investigated for use as aggregate in concrete (Vishwakarma 1994). Slump was not affected when 1 percent plastic was used regardless of particle size and shape; for 4 percent additions, the slump reduced by 10 to 77 percent, depending on
the shape and size. When very fine plastic vent dust was used, the cohesiveness was greatly improved. Concrete strength was greatly influenced by size and shape of filler, but strength was always reduced. Strength reduction was generally less when the filler size and shape was similar to the coarse aggregate than for finer sizes. Impact resistance on concrete specimens made with plastic filler as measured by the Los Angeles abrasion test was improved for only one plastic, high-density polyethylene fines. Concrete made with six of the eight plastics showed an increase in abrasion resistance when the amount of plastics was increased from 1 to 4 percent. The use of the plastics in concrete resulted in equal or lower scaling resistance (Akçaözoğlu et al. 2010; Yesilata et al. 2009; Remadnia et al. 2009; Marzouk et al. 2007; Vishwakarma 1994; Sander 1993).

4.5.7 Recycled scrap tire aggregates—Millions of scrap automotive tires are landfilled each year. They pose a fire hazard and a habitat for mosquitoes. Scrap tires in the form of crumb rubber have been proposed as aggregates for concrete. They have been used as a fine aggregate replacement and as an additive to the concrete mixture. With increasing rubber content:

(a) The workability as measured by slump decreases.

(b) The entrained air content increases; compressive strength decreases approximately 35 psi (240 kPa) per percent increase in crumb rubber when used as fine aggregate replacement.

(c) Flexural strength decreases approximately 5 psi (35 kPa) per percent increase in crumb rubber.

(d) The modulus of elasticity is reduced approximately 40 ksi (275 MPa) per percent increase in rubber.

(e) Permeability, as indicated by ASTM C1202, increased 66 coulombs per percent increase in crumb rubber (Ajibola 1994).

Because of its drawbacks, the only use of crumb rubber in concrete as a replacement of conventional aggregates to support sustainability would appear to be in the construction of applications such as walkways, cycling tracks, or pavements subjected to low loads (Ajibola 1994).

4.5.8 Recycled asphalt pavement aggregates—Recycled asphalt pavement (RAP) has been proposed for use as concrete aggregate, particularly in areas in which good-quality virgin aggregates are limited and to eliminate the placement of RAP into landfills. Research has been performed to use RAP as a replacement of the coarse and fine aggregate in concrete on an equal weight basis. With increasing RAP content, slump and air content increases; the compressive strength decreases approximately 80 psi (550 kPa) and flexural strength decreases approximately 8 psi (55 kPa) per percent increase in RAP; the modulus of elasticity decreases approximately 40 ksi (275 MPa) per percent increase in RAP; and permeability, as indicated by ASTM C1202, increases approximately 80 coulombs per percent increase in RAP (Ajibola 1994).

As with crumb rubber, RAP can be used in concrete to contribute to sustainability in applications in which low loads are applied and high-quality concrete is not essential. (Ajibola 1994)

4.6—Mineral filler

Mineral filler (MF) is a finely divided mineral product, at least 65 percent of which passes the No. 200 (75 μm) sieve. Gradation is given by ASTM C1797, clay/smectite content is indicated by AASHTO T 330, and chloride content by ASTM C1218/C1218M (optional).

In general, there are two different categories of MF: siliceous base and carbonate base. The siliceous MF is a by-product of crushing siliceous stone and is captured as dry fines or wet fines in aggregate quarry ponds. Most quarries producing crushed siliceous rocks will produce by-product fines. Production of this MF will vary among quarries depending on the type of rock and processing equipment. In general, siliceous materials are higher in hardness (Mohs hardness 7 or higher) and have high resistance to crushing. The use in concrete will help to reduce by-product and pond fines, and therefore improves sustainability. The energy to produce siliceous MF is similar to that required for crushing the siliceous stone and will depend on the type of rocks and equipment being used.

The carbonate MF, also called ground calcium carbonate (GCC) or calcium carbonate fines (CCF), is normally produced for various purposes including use in concrete. The GCC is available in dry and wet (slurry) form. Dry-powder GCC is more common for concrete applications. The most effective process is normally using ball mills and air classifiers.

Ground calcium carbonate is not hydraulic binder; however, it can provide nucleation sites for cement hydration and accelerating the development of C-S-H phases at early ages. (Hooton et al. 2007; Tennis et al. 2011; Schmidt 1992a,b; Hawthorn 1993; Mikhailova et al. 2013).

There are no data available to quantify the energy reduction in the concrete-making process with and without mineral filler. It is easier to handle concrete with more paste and mortar compared to mixtures that lack the desired workability and consistency due to a deficiency of mortar or aggregate fines, and it is intuitive that less energy is required for placement and finishing.

The use of mineral filler has been studied for many years. In practice, MF is used to replace sand, coarse aggregate, or both, by up to 20 percent. When properly proportioned, mineral fillers can be used to reduce the consumption of cement while keeping the workability and strength to the target strength of concrete (Juenger et al 2006). The use of MF in concrete can be economically beneficial, saving energy and reducing CO₂ emissions, thereby contributing to sustainability (Juenger et al. 2006; Fowler and Quiroga 2004).

CHAPTER 5—CHEMICAL ADMIXTURES AND ADDITIVES

5.1—Overview

A chemical admixture is a material that is used as an ingredient in a cementitious mixture such as concrete, mortar, or grout, usually in small quantities to modify one or more of the properties of the mixture in the fresh or hardened state.
Table 5.3a—Potential environmental impacts of chemical admixtures per kg of admixture

<table>
<thead>
<tr>
<th>Admixture type</th>
<th>Solids content, percent</th>
<th>Typical dosage, percent of cement</th>
<th>GWP</th>
<th>ODP</th>
<th>AP</th>
<th>POCP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retarders</td>
<td>10 to 60</td>
<td>0.2 to 2.0</td>
<td>1.31</td>
<td>3.50E-10</td>
<td>1.04E-02</td>
<td>6.73E-04</td>
</tr>
<tr>
<td>Set accelerators</td>
<td>10 to 70</td>
<td>1.0 to 3.0</td>
<td>1.33</td>
<td>1.80E-10</td>
<td>2.56E-03</td>
<td>3.64E-04</td>
</tr>
<tr>
<td>Air entrainers</td>
<td>5 to 13</td>
<td>0.05 to 1.0</td>
<td>5.27E-01</td>
<td>7.56E-11</td>
<td>1.30E-03</td>
<td>3.45E-04</td>
</tr>
<tr>
<td>Hardening accelerators</td>
<td>10 to 70</td>
<td>1.0 to 3.0</td>
<td>2.28</td>
<td>1.74E-10</td>
<td>6.60E-03</td>
<td>4.84E-04</td>
</tr>
<tr>
<td>Plasticizers/high-range water-reducing admixtures</td>
<td>30 to 45</td>
<td>0.2 to 2.0</td>
<td>1.88</td>
<td>2.30E-10</td>
<td>2.92E-03</td>
<td>3.12E-04</td>
</tr>
</tbody>
</table>

For fresh concrete, chemical admixtures are typically used to reduce mixture water content, entrain air, increase workability, reduce segregation, control rate of bleeding, reduce rate of slump loss, improve pumping, improve finishing, control time of setting, or a combination of these. The potential benefits of chemical admixtures in the hardened state include increased strength, impact and abrasion resistance, improved aesthetics, reduced drying shrinkage and permeability, and an overall increase in durability (ACI 212.3R).

Chemical admixtures are governed by several industry standards, but the predominant and most widely used standards are ASTM C260/C260M and ASTM C494/C494M.

A review of their benefits shows that chemical admixtures play an important role in the construction of environmentally friendly, sustainable concrete structures, while helping to conserve natural resources. Admixtures can contribute to the embodied energy and emissions or consume raw materials. The typical dosage used, however, is low and the benefit in terms of fresh or hardened properties of the concrete is significant. Accordingly, the sustainability benefits of their use can be great. The benefits of chemical admixtures with respect to sustainability in concrete construction are discussed in the sections that follow.

5.2—Materials used in admixture formulations

Materials used in chemical admixture formulations vary depending on type and may be derived from natural material sources, by-products of other manufacturing processes, or synthetic. For example, the basic ingredients used in water-reducing and retarding admixtures—corn syrup and lignosulfonates—have for decades been obtained from corn or wood. In addition, lignosulfonates are by-products from the production of wood pulp using the Kraft Process (Driessen et al. 2000; Mockos et al. 2008). Polycarboxylate ethers and polyvinyl copolymers, the primary materials currently used in the high-range water-reducing admixture formulations and pozzolanic-based cement activators are synthesized materials. Details on the types of raw materials used in chemical admixtures are given in ACI 212.3R.

5.3—Environmental impact

Chemical admixtures can affect the environment both during their manufacture and in concrete mixtures. The manufacture of a chemical admixture typically only requires blending of its constituent materials prior to shipment. Note, however, that processing of the constituent materials can be more complex than just blending, which can result in a potentially higher environmental footprint upstream. An admixture Environmental Product Declaration (EPD) captures all the environmental impacts from all processes from raw material extraction through final manufacturing.

With respect to application, chemical admixtures generally constitute a very small fraction of the total volume or mass of concrete—usually less than about 0.2 percent of concrete volume for most admixtures and up to about 3.0 percent for some corrosion inhibitors and permeability-reducing admixtures. Therefore, the contribution of chemical admixtures to the environmental impact of a concrete mixture is typically low relative to other concrete-making materials.

Although chemical admixtures fall below typical cutoff criteria by mass or energy use for a life-cycle assessment (LCA) of concrete, they may still contribute to a concrete’s environmental impact. The European Federation of Concrete Admixture Associations (EFCA) has reported environmental impacts of chemical admixtures through EPDs for different types of chemical admixtures taking into consideration the environmental impact from cradle-to-gate production (EFCA 2015). Table 5.3a provides results for some of the key environmental impacts from chemical admixture production per unit of admixture, while Table 5.3b reports the key environmental impacts from chemical admixture production per unit of concrete produced. The environmental impacts in terms of global warming potential (GWP), depletion potential of the stratospheric ozone layer (ODP), acidification potential of land and water (AP), and formation potential of tropospheric ozone photochemical oxidants (POCP) are included. Note that the EFCA-validated declarations exclusively apply to plants operated in Belgium, France, Germany, Italy, Netherlands, Norway, Spain, Sweden, Switzerland, Turkey, and the United Kingdom by EFCA National Association members and are provided only for informational purposes.

Chemical admixtures in and of themselves contribute very little to the total environmental burden of concrete. This addition is dwarfed by the net reduction in the environmental impacts of concrete that use of chemical admixtures can provide.

The data show that on a cubic meter basis, the GWP, for example, associated with chemical admixtures is small. Even at the high end of the typical dosage range, the potential CO$_{2\text{eq}}$ emissions associated with a hardening accelerator admixture...
Water-reducing admixtures enable increased amounts of SCMs, such as fly ash, metakaolin, and slag cement, as partial replacements for portland cement. As discussed previously, the overall benefit of using supplemental cementitious materials (SCMs) in concrete is a net reduction in the embodied energy and greenhouse gas (GHG) emissions associated with the production of portland cement. In this regard, water-reducing admixtures provide a net sustainability benefit.

As reported in Marceau et al. (2007) and shown in Fig. 5.4.1, the embodied energy of concrete can be reduced through partial replacement of portland cement with SCMs, such as fly ash and slag cement. To offset the potential adverse effects of increased levels of SCMs on time of setting and early-age strength development, chemical admixtures—specifically mid- and high-range water reducers in conjunction with accelerating admixtures—are typically used.

In high-strength concrete applications, high-range water-reducing admixtures are needed to produce workable concrete mixtures at the low w/cm required to achieve the desired strengths. The use of high-strength concrete can result in smaller member sizes that would invariably require less concrete; less concreting materials overall; and, consequently, conservation of natural resources, even though cementitious materials content in a mixture may be higher.

5.4.2 Reduction in water use—Concrete is a very efficient material in terms of water use at approximately 3 L/liter per kg (Ashby 2012); however, the large quantity of concrete used globally makes reducing this quantity important. The use of water-reducing admixtures is one way to reduce the water consumed in concrete production and, as such, will contribute to water conservation while maintaining fresh, hardened, and plastic concrete properties. As required by ASTM C494/C494M, normal and high-range water-reducing admixtures must reduce mixing water content by a minimum of 5 and 12 percent, respectively. Most high-range water-reducing admixtures, however, provide up to 30 percent water reduction and, depending on type and application, up to 40 percent water reduction for polycarboxylate ethers in self-consolidating concrete, for example. The data in Fig. 5.4.2 show that high-range water-reducing admixtures have provided increased levels of savings in mixture water use within the U.S. concrete industry since the mid-1980s. The data plotted in Fig. 5.4.2 were estimated using industry data for concrete production and high-range water-reducing admixture usage, and assuming a modest water reduction of 20 percent. The data do not include the mixing water content savings derived from the use of normal and mid-range water-reducing admixtures.

### Table 5.3b—Potential environmental impacts of chemical admixtures per m$^3$ of concrete mixture*

<table>
<thead>
<tr>
<th>Admixture type</th>
<th>Solids content, percent</th>
<th>Typical dosage, percent of cement</th>
<th>GWP kg CO2-Eq</th>
<th>ODP kg CFC 11-Eq</th>
<th>AP kg SO2-Eq</th>
<th>POCP kg ethene-Eq</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retarders</td>
<td>10 to 60</td>
<td>0.2 to 2.0</td>
<td>8.78</td>
<td>2.35E-09</td>
<td>0.070</td>
<td>4.51E-03</td>
</tr>
<tr>
<td>Set accelerators</td>
<td>10 to 70</td>
<td>1.0 to 3.0</td>
<td>13.37</td>
<td>1.81E-09</td>
<td>0.026</td>
<td>3.66E-03</td>
</tr>
<tr>
<td>Air entrainers</td>
<td>5 to 13</td>
<td>0.05 to 1.0</td>
<td>1.77</td>
<td>2.53E-10</td>
<td>0.004</td>
<td>1.16E-03</td>
</tr>
<tr>
<td>Hardening accelerators</td>
<td>10 to 70</td>
<td>1.0 to 3.0</td>
<td>22.91</td>
<td>1.75E-09</td>
<td>0.066</td>
<td>4.86E-03</td>
</tr>
<tr>
<td>Plasticizers/ high-range water-reducing admixtures</td>
<td>30 to 45</td>
<td>0.2 to 2.0</td>
<td>12.60</td>
<td>1.51E-09</td>
<td>0.020</td>
<td>2.09E-03</td>
</tr>
</tbody>
</table>

*Assuming 30 MPa (4350 psi) concrete mixture with 335 kg/m$^3$ (565 lb/yard$^3$) of cementitious materials and high end of dosage range for each admixture type.

Fig. 5.4.1—Effect of SCMs on embodied energy of concrete (Marceau et al. 2007).
Figure 5.4.2—Estimated annual water savings due to use of high-range water-reducing admixtures in U.S. concrete industry (Nmai 2013). (Note: 1 gal. = 3.785 L.)

Figure 5.4.2 indicates that high-range water-reducing admixture use in the U.S. concrete market alone provides an annual savings of approximately 500 million gal. (1.9 billion L) of water. Taking into account the water savings derived from the use of normal and mid-range water-reducing admixtures, the total annual water savings provided by all water-reducing admixtures is estimated to be approximately 1 billion gal. (4 billion L).

**5.4.3 Improvement to concrete durability**—One of the principal factors affecting the durability of concrete is its permeability, which is influenced by, among other things, w/cm, SCMs, and chemical admixtures. High-range water-reducing admixtures, in particular, facilitate the production of workable low-w/cm concrete mixtures with low diffusion coefficients and low permeability (Fig. 5.4.3). A reduction in permeability and other fluid transport properties help to minimize the intrusion of aggressive chemicals such as chlorides and sulfates and improve the corrosion and sulfate resistance of concrete.

Latex-based admixtures also provide significant reductions in concrete permeability and are typically used in bridge deck applications to reduce chloride ingress from the application of deicing chemicals.

In aggressive environments, concrete durability can be significantly improved through the use of durability-enhancing admixtures such as air entrainers, corrosion inhibitors, permeability-reducing admixtures, lithium-based admixtures, and shrinkage reducers. Developed in the mid-1930s, air entrainers are used to develop a finely-divided system of air bubbles to increase the resistance of concrete to deicer salt scaling and damage from cyclic freezing and thawing. Corrosion inhibitors are used to increase protection for steel reinforcement in concrete exposed to chlorides in service and thereby help to achieve design service lives. Since the 1960s, permeability-reducing admixtures have been developed to improve concrete durability through controlling water and moisture movement and associated dissolved salts and other aggressive agents (Aldred 1989; Roy et al. 1999; ACI 212.3R). In geographic areas where the aggregates may be prone to alkali-silica reaction (ASR), lithium-based admixtures can be used either solely or in combination with pozzolans or slag cement to mitigate the reaction and prevent the destructive cracking associated with it. Shrinkage reducers have been used in concrete since the mid-1980s to reduce the magnitude of autogenous/drying shrinkage and related issues such as cracking and curling in slabs. Increasingly, shrinkage reducers are being used to improve water tightness in water-retaining structures and to reduce midpanel cracking and joint deterioration in slabs. The use of lithium-based admixtures and shrinkage-reducing admixtures allow the use of aggregates indigenous to a region that otherwise may be rendered unusable in construction. Using regional materials lowers the economic burden of transporting aggregates from other areas, as well as lowering the embodied energy from transportation of aggregates.

Overall, durability-enhancing admixtures and SCMs can be used to help produce concrete mixtures for long design service lives, such as 75 to 100 years for bridges, in aggressive environments. The use of chemical admixtures to further enhance concrete durability and achieve longer design service lives will, therefore, minimize the need for major repairs and replacement of concrete structures due to premature deterioration. In this regard, one of the net benefits of using chemical admixtures to achieve greater design service lives is conservation of natural resources.

**5.4.4 Improvement in the solar reflectance index of concrete**—For materials with the same thermal emittance, surfaces that are darker in color absorb heat and require additional illumination whereas lighter colored surfaces reflect heat and require less illumination, thereby minimizing energy demands both for cooling and lighting as well as reducing the heat island effect of concrete surfaces. Consequently, concrete surfaces can provide energy savings relative to asphalt by virtue of the lighter color of concrete.

Fig. 5.4.3—Effect of w/c on permeability (Neville and Brooks 1987).
Research has shown that typical gray concrete, without added pigments, can meet USGBC LEED (United States Green Building Council Leadership in Environmental and Engineering Design) requirements for solar reflective index (SRI) (Marceau and VanGeem 2007). Liquid-coloring admixtures and pigments, which are used in concrete for aesthetic purposes, can also be used to further increase the SRI of concrete, depending on the specific color or pigment. As an alternative to the use of white cement or high-slag cement, titanium dioxide (TiO₂) has also been used to lighten gray cement and increase the SRI of concrete. TiO₂ is one of the four most common types of pigments used in coloring concrete with the others being iron oxide pigments, chrome oxides, and cobalt blue pigments. Most manufacturers provide an SRI value for pigments used in concrete.

5.5—Reducing concrete waste

The disposal of returned plastic concrete and concrete washwater is an environmental challenge for concrete producers. According to the National Ready Mix Concrete Association (NRMCA 2018), approximately 2 to 10 percent (average 5 percent) of ready mixed concrete produced in the United States is returned to the concrete plant (Obla et al. 2007). With overall production reaching 351 million yd³ (268 million m³) (NRMCA 2018) there are approximately 18 million yd³ (13 million m³) of returned concrete processed annually. Concrete waste can be reduced by reducing the perishability of fresh concrete and by managing the disposal of returned plastic concrete and concrete washwater. The perishable nature of fresh concrete can be reduced through the use of retarding admixtures and workability-retaining admixtures that help to maintain slump and workability for longer periods of time, facilitating placement.

Chapter 6 will detail the aspects of water used as a reagent in concrete. This section will deal with admixtures to treat water at the plant. Concrete waste and washwater can be effectively managed through the use of hydration-controlling admixtures (HCAs) and may also be known as extended-set control admixtures (ACI 212.3R) or hydration-stabilizing admixtures (ASTM C1798/C1798M). Hydration-controlling admixtures are a highly potent class of retarding admixtures that provide effective control over the hydration of hydraulic cement and delay the time of setting of concrete over extended periods to facilitate long-haul applications, address delays, and slow concrete placements. As a result, HCAs provide significant benefit by reducing the perishable nature of concrete and help to minimize, if not eliminate, rejected loads due to workability loss. The use of HCAs for these applications will require a waiver of typical restrictions on time to total discharge and maximum drum revolutions.

Hydration-controlling admixtures are also used to effectively manage returned plastic concrete and concrete washwater (Ragan and Gay 1995). With respect to returned plastic concrete, depending on time after batching, concrete, and ambient temperatures, HCAs can be used to stabilize returned concrete and later blended with fresh concrete prior to use in another application (ASTM C1798/C1798M). In blending new and returned concretes, the plastic and hardened properties of the blended concrete are dependent on the percentage of concrete returned used and its age (Lobo et al. 1995; Lobo and Gaynor 1998). The use of HCAs to stabilize returned plastic concrete diverts such concretes from being disposed of in landfills or more energy-intensive recycling of hardened concrete. Hydration-controlling admixtures can also be used to stabilize concrete washwater in truck drums. The stabilized washwater can then be used in subsequent loads, with a corresponding reduction in the mixture water batched into the concrete. In addition to reducing or eliminating the disposal of concrete washwater, stabilization of concrete washwater also uses less water than is typically required to clean the drums of concrete trucks.

The use of HCAs to stabilize fresh concretes for long-haul applications, returned plastic concrete for same-day or overnight applications, and concrete washwater effectively helps to reduce construction waste while addressing environmental issues associated with the disposal of concrete waste and washwater, thereby reducing landfill waste.

CHAPTER 6—WATER

6.1—Overview

Concrete production relies on the use of water. The unit consumption of water for concrete is low in comparison to other building materials, as shown in Fig. 6.1 (Ashby 2012). Although the unit consumption of water is low, the large quantity of concrete made worldwide makes efforts to reduce this quantity important. Potable water is the preferred water for making concrete. Water is used in the manufacture of concrete mixtures, during curing of the concrete, and to clean out the truck drums after delivery of concrete. This chapter reviews the standards for water as a constituent material in concrete mixtures and presents strategies for reducing the amount of potable water in concrete mixtures.

6.2—Standards for water in concrete mixtures

Research on the effect of process water on ready mixed concrete (Lobo and Mullings 2003) has been conducted in the United States and other countries (Sandrolini and Franzoni 2001; Rickert and Grube 2003; The New Zealand Ready Mixed Concrete Association Inc. 2006). Research indicates that process water, referred to as water from concrete production, as well as other sources of nonpotable water, have been permitted in many national standards, including ASTM International. Testing is used to ensure it has minimal adverse effects on concrete performance.

ASTM C94/C94M specifies that water used in concrete mixture proportion shall conform to ASTM C1602/C1602M. ASTM C1602/C1602M states that potable water can be used without testing. Nonpotable water, which includes wells, streams, or other water-retention areas, and process water, when combined with other sources of water, should be tested for 7-day compressive strength and time of initial set (Table 6.2a).

Comparisons are based on fixed proportions for a concrete mixture made with the unknown water supply and a control mixture using 100 percent potable water or distilled water.
Similar performance, within limits set in the specification, compared with a control concrete mixture containing potable water should be attained. The water source should be tested before initial use. Optional limits for the combined mixing water exist for alkalis, sulfates, chlorides, and total solids by mass (Table 6.2b) where warranted by anticipated exposure conditions and type of construction.

Testing frequency is permitted to be reduced to once every month when the results of 2 months of consecutive tests indicate compliance with the requirements of Table 6.2a. Testing frequency to qualify water increases as mixing water with higher solids content (specific gravity greater than 1.0) is intended to be used.

ASTM C1603 provides a method to establish a relationship between the measured relative density and solids content of water sample for a range of solid concentrations that cover the anticipated solids content range in the plant. From this relationship, the relative density measured during regular production can be used to quantify the solids content in the process water. If such a relationship is not developed, ASTM C1603 suggests simplified equations that relate solids content and relative density. The appendix of ASTM C1603 provides some guidance on blending two sources of water to comply with target solids.

6.3—Strategies for reducing consumption of potable water in production of concrete

There are several strategies that can be implemented to reduce the consumption of potable water in the production of the concrete mixture. The following strategies provide means to reduce use of potable water in the production of concrete.

Reduce cementitious material content in the mixture design. One simple way to reduce the demand for potable water in concrete mixtures is to reduce the cementitious materials content in the mixture. A few examples of how cementitious content can be reduced include:

(a) Use efficient design practices that minimize possible overdesign of structural elements in terms of strength, durability, and the owner’s intended design life for the structure.

(b) Minimize the use of cementitious materials and supplementary cementitious materials (SCMs) as filler in the concrete mixture through optimizing gradation of aggregate in the mixture.

(c) Specify high-performance concrete where justified by project design parameters. Almost to the contradiction of reducing cementitious material content, there will...
be instances where providing a very durable structure are justified. In these instances, reducing the \( w/cm \) may improve durability characteristics as well reducing the demand for water in the concrete mixture. In addition, specifying high-performance concrete may allow the designer to reduce the size of members, which in turn reduces total amount of materials, including water that is consumed.

(d) Incorporate water-reducing admixtures in the mixture proportion, which is currently the most common strategy for reducing the water content of concrete.

(e) Incorporate internal curing in the process. Use nonpotable mixing water in place of potable mixing water. Sources of nonpotable water include recovered and reused process water from the concrete production and batching process. The topic of recovering and reusing nonpotable water from the concrete operation is discussed in detail in Chapter 6.

6.4—Summary

6.4.1 Reducing water consumption—The basic sustainability challenge is that the best water for concrete is the water used for human consumption, which is in diminishing supply. Despite the low unit water consumption in the manufacture and use of concrete, reducing the amount water used in the process of manufacturing concrete through reuse of process water and other nonpotable sources increases its sustainability.

6.4.2 Solutions—The concrete industry has the potential to reduce the volume of potable water used in concrete mixtures by using available nonpotable water sources, aligning design parameters to the intended use and expected life of the structure, and by implementing various equipment use technologies and production processes at production facilities to create new sources of nonpotable water. The policies, procedures, methods, and materials adopted by the concrete industry should still be consistent with durable and sustainable concrete products.

CHAPTER 7—REINFORCEMENT

7.1—Introduction

Reinforcing materials are an integral part of most concrete structures. While fiber-reinforced polymers are well described (ACI 440R), most structures use steel reinforcement. In reinforced concrete structures, the reinforcement is necessary to overcome the low tensile strength of concrete. Although modern steel typically contains a high percentage of recycled material, this reinforcement still adds its own environmental impacts to concrete structures. An example is embodied energy as shown in Fig. 7.1.

Typically, most reinforcing materials consist of deformed steel bars and wires. More recently, however, new materials such as stainless steel deformed bars, glass fiber bars, and carbon fiber sheets have been used in several applications. Additionally, small fibers of steel, glass, and other synthetic materials uniformly dispersed through the concrete matrix have been successfully used to produce desired properties, often together with steel reinforcement. Generally, reinforcement should have the following properties for durable concrete construction:

(a) High strength
(b) Sufficient bond to the concrete matrix
(c) Thermal compatibility to the concrete matrix
(d) Durability from elements in the concrete matrix and from elements to which the concrete could be exposed

ACI 318 and ACI 301 provide code requirements for reinforcing amount, spacing, concrete cover, and best practices to minimize cracking of the concrete and prevent corrosion of the reinforcing material. Corrosion of reinforcing materials is a major cause of concrete deterioration. Many
materials and strategies are available to designers to protect internal reinforcing from corrosion.

In this chapter, different types of reinforcing and their corrosion-resistant properties are discussed.

7.2—Steel reinforcement

Steel reinforcement typically contains a high percentage of recycled material content and is highly recyclable at the end of the usable service life of the structure. The ability to recycle steel reinforcement easily enables the manufacturing of new steel products from old steel reinforcement, thus minimizing waste.

The Concrete Reinforcing Steel Institute (2009) has provided the following information regarding the recycled content of steel reinforcement:

The vast majority of domestically produced, conventionally available reinforcing steel has a recycled material content typically greater than 97 percent (ASTM A615/A615M, ASTM A706/A706M). Specialty reinforcing steel products, such as ASTM A1035/A1035M low-carbon, chromium steel, and ASTM A955/A955M stainless steel, have a recycled content typically greater than 75 percent.

Welded wire reinforcement is typically produced with 92 to 97 percent recycled material content.

7.3—Steel reinforcing bars

The standard specifications for steel reinforcement published by ASTM International are generally accepted for construction in the United States. ASTM A615/A615M and ASTM A706/A706M are presently the most common steel reinforcing bars used for reinforced concrete construction. Both ASTM A615/A615M and ASTM A706/A706M specifications include Grade 60 (yield strength of 60 ksi [420 MPa]) and Grade 80 (yield strength of 80 ksi [560 MPa]) and Grade 100 (yield strength of 100 ksi [700 MPa]); however, Grade 60 (yield strength of 60 ksi [420 MPa]) material is currently the most commonly used strength grade, representing over 90 percent of all grades of reinforcing steel products (Concrete Reinforcing Steel Institute 2009). ASTM A615/A615M does include Grade 40 (yield strength of 40 ksi [280 MPa]), a material predominantly used in residential construction, and Grade 75 (yield strength of 75 ksi [525 MPa]) which, after a transition period, will be replaced by Grade 80 (yield strength of 80 ksi [560 MPa]).

ASTM A996/A996M is for unique materials that are produced by reusing, rather than recycling, steel rails and train axles. The rails and axles are simply reheated and rerolled into reinforcing steel products. Rail-steel and axle-steel reinforcing bars are not generally available except in a few areas of the country. In those areas where such bars are currently available, not all bar sizes and grades are produced and furnished. Before specifying ASTM A996/A996M reinforcement, local availability should be investigated (Concrete Reinforcing Steel Institute 2009).

ASTM A1035/A1035M is for a relatively new series of very-high steel reinforcing materials. ACI 318 has adopted the limited use of ASTM A1035/A1035M Grade 100 (yield strength of 100 ksi [700 MPa]) material for use as confinement reinforcement such as ties or spirals in compression elements.

The use of higher-strength Grade 80 (yield strength of 80 ksi [560 MPa]) and Grade 100 (yield strength of 100 ksi [700 MPa]) reinforcing products can, in some instances, allow reductions in the required cross-sectional area of reinforcing steel. If such replacements can be accomplished, financial and environmental impact savings can be realized, resulting from the reduction in material requirements and in fabrication and transportation logistics from the potential reduction in structural mass (if member size can be reduced).

7.3.1 Corrosion protection strategies—Corrosion protection of concrete structures is a system of strategies aimed at minimizing the exposure of the reinforcing steel to corrosive elements, improving the corrosion protection of the concrete matrix, and the use of coatings or alternate chemistries to protect the reinforcing steel. Proving durability from corrosion can significantly increase the life cycle of a concrete structure, increasing its service life and reducing the impacts of costly and disruptive repairs.

Coatings specified by ASTM A775/A775M and ASTM A934/A934M provide a barrier to protect the reinforcing steel bars from corrosive elements and to interrupt the formation of corrosive galvanic cells. ASTM A767/A767M specifies the coating of reinforcing bars to provide both a sacrificial protective layer and a barrier to corrosive elements, thereby protecting the underlying steel. ASTM A1055/A1055M incorporates a thermally sprayed zinc coating and an epoxy coating to provide an additional level of protection using two different strategies for protecting the reinforcing steel.

Stainless steel reinforcing bars specified by ASTM A955/A955M are made from steel alloys that are significantly more resistant to the corrosive elements, mainly chlorides and carbonation, typically associated with reinforcing steel. Stainless-steel-clad reinforcing bars, which are not covered by ASTM specifications, have limited availability. As these materials are currently not produced in the United States, transportation logistics and associated environmental impacts should be carefully evaluated.

7.4—Welded-wire reinforcement

Welded-wire reinforcement is used to control crack widths, resulting in lower maintenance for concrete slabs. As stated previously, the recycled content of steel reinforcement is typically 92 to 97 percent. Produced in accordance with ASTM A1064/A1064M, welded-wire reinforcement is available in yield strengths between 60 to 80 ksi (420 to 560 MPa). Using material with higher yield strength, it may be possible to reduce the total amount of reinforcing steel needed, thus reducing the environmental impacts resulting from material savings, and reduced production and transportation logistics.

7.4.1 Corrosion protection strategies—Steel conforming to ASTM A884/A884M incorporates a protective barrier to corrosive elements and interrupts the formation of corrosive galvanic cells to protect the underlying steel. Stainless steel
bars that conform to ASTM A1022/A1022M are also available and can be used as part of a corrosion protection strategy.

7.5—Fiber reinforcement

Steel bars or welded wire have been the common reinforcement materials for more than a century; however, a bar reinforces the concrete only in the direction in which it is oriented. Numerous uniformly dispersed and randomly oriented short fibers, on the other hand, strengthen the material in any direction more or less equally, literally changing the properties of the composite material itself (Chawla et al. 2013; Chawla 2016).

Most fiber reinforcement dosages are 1 percent of the concrete volume or less. At such dosages, the strengthening effect of fibers is not substantial, and if the elastic modulus of the fiber is less than that of the concrete, such as with polypropylene fiber, it can be negative. Once a crack of the concrete matrix opens, it is likely to be bridged by only a small number of fibers with a combined strength unlikely to exceed that of the concrete matrix. However, the large amount of work needed to either fracture the fiber reinforcement or to pull the fibers out of the matrix can increase the ductility and fracture energy by an order of magnitude. This is particularly true if the fiber aspect ratio and other design parameters are carefully selected to result in multiple cracks forming along a single fiber and thereby provide strain hardening. In this case, the composite is referred to as high-performance fiber-reinforced cement composite (Naaman and Reinhardt 1996).

In these materials, the primary function of the fibers is to control cracking, and not to increase the compressive or tensile strength of the composite. By keeping the cracks small, the permeability and, therefore, the durability of the composite is greatly improved, which in turn increases its sustainability. Another way to increase the durability of the fiber composite is to combine two or more different types of fibers, each of which controls cracking of the cement matrix on a different length scale (ACI 544.1R).

Fiber dosages exceeding 1 percent by concrete volume are likely to impair the workability of the mixture and potentially increase fiber balling. To counteract these negative effects, the fibers may be preplaced within the formwork, with cement slurry added afterward to infiltrate all void spaces. The result is the so-called slurry-infiltrated fiber concrete.

7.5.1 Steel fibers—Steel fibers are among the most widely used short fibers. Steel fiber-reinforced concrete fails only after the fibers break or are pulled out from the cement matrix. By changing their aspect ratio (that is, length-to-diameter ratio) or by changing their surface properties, it is possible to control the failure mode. Shorter fibers may be used and still delay fiber pullout by adding hooks at the fiber end, crimping the fibers, or adding other deformations that increase the bond strength between the fibers and cement matrix. ACT 318 allows the use of steel fibers for shear reinforcement.

7.5.2 Synthetic fibers—There exist a multitude of synthetic fibers, most of them of polymeric in nature. The most common materials are polypropylene, polyethylene, polyvinyl alcohol (PVA), nylon, and polyester. Most of these materials have a relatively low melting point, which makes them vulnerable when exposed to elevated temperatures, as in the case of fire. However, melting fibers has been shown to increase resistance to explosive spalling in fires by providing pathways for steam to escape.

7.5.3 Glass fibers—Glass fibers are very popular in the façade element industry, but glass and similar amorphous compounds tend to be attacked by the alkaline cement matrix, which is similar to alkali-silica reaction, thus weakening and eventually fracturing the fibers. To make glass fibers more alkali-resistant (AR-glass), manufacturers typically add zirconium to the glass melt.

7.5.4 Basalt fibers—Basalt fiber is obtained by drawing the molten natural occurring basalt rock into thin continuous glassy filaments of 9 to 15 μm diameter. Despite their brittle nature, the small size of the fibers limits the dimension of flaws in the material so that tensile strengths as high as 215 to 430 ksi (1500 to 3000 MPa) can be obtained. Although their availability is still limited, the high strength, high-temperature resistance, and low cost are expected to increase their popularity.

7.5.5 Natural fibers—Natural fibers are renewable, having a minimum amount of embodied energy, and instead of releasing CO₂ into the atmosphere, they can actually absorb or sequester carbon. Some of the materials that have been used as reinforcement of concrete are sisal, kenaf, hemp, coconut, jute, flax, sugar cane bagasse, and bamboo as individual fibers, strips, and bars. All these natural materials are vulnerable to chemical reactions with the alkaline cement matrix, moisture, or both, deteriorating their material properties over time. These fibers require protection against such reactions by suitable treatments. ACI 544.1R contains a summary and an extensive reference section on natural fibers.

7.6—Nonferrous reinforcement

7.6.1 Carbon fiber reinforcement—A recent development in nonferrous reinforcing is the development of carbon-fiber reinforcing. Made of thin fibers of carbon (0.005 to 0.010 mm in diameter), carbon fiber has a very high tensile strength of 250 ksi (1.75 GPa), or approximately four times the tensile strength of conventional reinforcing bars. Previously, carbon fiber was used primarily in the aerospace and sports equipment industries. Now it is manufactured in sheets or grids/mesh for the concrete industry. The grids or mesh are manufactured by using epoxy to hold carbon fibers interlaced together in two directions. Carbon fiber’s noncorrosive and nonconductive properties provide greater potential for more sustainable concrete design and construction. Examples for common uses are shown in 7.6.1.1 through 7.6.1.3.

7.6.1.1 Precast insulated sandwich wall panels—Carbon fiber grid is cut into strips to tie an outer wythe of concrete to an inner wythe of concrete with a middle layer of insulation sandwiched between. Previous methods using steel trusses required more concrete cover to protect against corrosion and the steel trusses themselves are a source of thermal bridging that reduces the overall insulating value of the wall panel. Precast sandwich wall panels with carbon fiber ties are being manufactured with thinner concrete sections...
that reduce materials, energy consumed, and energy associated with transportation by the corresponding reductions in weight. Reduction in thermal bridging also results in higher thermal performance of the building envelope, which lowers the HVAC energy used by the building.

7.6.1.2 Precast double tees in parking structures—Some precast double-tee members commonly used in parking structures are now using carbon fiber mesh for the flange deck reinforcement in place of traditional steel mesh. Carbon fiber’s noncorrosive properties enable the double-tee flange to be thinner, thus saving concrete and lightening the overall structure, which may also reduce the size of the required support and foundation. Reduced damage due to corrosion in a parking deck also means that the structure will be more durable and have a longer life cycle.

7.6.1.3 Seismic retrofitting and repairs—Carbon fiber sheets and wraps can be applied to existing concrete structures with epoxy. Glass fiber can also be used in this method. It is being used to strengthen existing concrete columns to resist earthquake forces and for repair of deteriorating concrete structures. By repairing structures and extending their life, the improved life cycle of concrete greatly contributes to sustainability.

CHAPTER 8—CONCLUSION

The initial selection of construction materials may depend on numerous complex and often intangible factors, but the total initial and long-term cost of using any construction material is one of the most important parameters. Environmental and economic evaluations are necessary components in identifying, assessing, and selecting building material. When used in combination with service life performance requirements, these factors provide a balance of economic, environmental, and societal impacts for material selection.

Infrastructure and building systems represent an enormous investment of materials, energy, and capital, resulting in significant environmental impacts and social costs. Development of innovative materials, construction practices, and employment of appropriate inspection and maintenance strategies is critical to ensure reduced environmental impacts, adequate safety, serviceability, and extended service life that minimizes the risk of failure for structures and infrastructure. Design, construction, maintenance, climate adaptation, and resiliency are all considerations that contribute to the overall sustainability of new assets. Hence, enhancing the resilience of infrastructure through designed robustness, durability, longevity, disaster resistance, and safety should also be a priority for the designer and engineer.

CHAPTER 9—REFERENCES

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ACI 212.3R-16—Report on Chemical Admixtures for Concrete

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ASTM International

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