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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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_2O) 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_2e. CO_2e is a measurement used to normalize the emissions from various greenhouse gases based on their global warming potential (GWP). CO_2e are commonly expressed as terragrams of carbon dioxide equivalents (a terragram is 1 million metric tons). The CO_2e for a gas is derived by multiplying the tons of the gas by its associated GWP, thus: $TgCO_2Eq = (Gg\ of\ gas) \times (GWP) \times (Tg/1000Gg)$. (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-