

ACI 130R-19

Report on the Role of Materials in Sustainable Concrete Construction

Reported by ACI Committee 130



American Concrete Institute
Always advancing



Report on the Role of Materials in Sustainable Concrete Construction

Copyright by the American Concrete Institute, Farmington Hills, MI. All rights reserved. This material may not be reproduced or copied, in whole or part, in any printed, mechanical, electronic, film, or other distribution and storage media, without the written consent of ACI.

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI via the errata website at <http://concrete.org/Publications/DocumentErrata.aspx>. Proper use of this document includes periodically checking for errata for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided “as is” without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Participation by governmental representatives in the work of the American Concrete Institute and in the development of Institute standards does not constitute governmental endorsement of ACI or the standards that it develops.

Order information: ACI documents are available in print, by download, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised the ACI Collection of Concrete Codes, Specifications, and Practices.

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Report on the Role of Materials in Sustainable Concrete Construction

Reported by ACI Committee 130

Julie K. Buffenbarger, Chair
Kevin A. MacDonald, Vice Chair

John T. Kevern, Secretary

Thomas H. Adams
James M. Aldred
Khaled Walid Awad
Nemkumar Banthia
Laurent Barcelo
Florian G. Barth
Mark F. Chrzanowski
Larry D. Church

Barry A. Descheneaux
David W. Fowler
Dean A. Frank
James K. Hicks
R. Doug Hooton*
Lionel A. Lemay
Emily B. Lorenz
Zoubir Lounis

Tracy D. Marcotte
Christian Meyer
Theodore L. Neff
Charles K. Nmai
Lawrence C. Novak
Matthew A. Offenberg
John P. Ries
John W. Roberts

Tonatiuh Rodriguez-Nikl
Larry Rowland
Koji Sakai
Arezki Tagnit-Hamou
Peter C. Taylor
Jeffrey S. Volz
Jeffrey S. West
Peter T. Yen

Subcommittee Members

Eckart R. Buhler
Yogini S. Deshpande
Ashish Dubey
Moetaz Maher El-Hawary
Alfred Gardiner
William Gaspar
Daniel J. Huffman

Per A. Jahren
Sam R. Johnson
Maria G. Juenger
Tyler Ley
Darmawan Ludirdja
Sean Monkman
Charles E. Pierce

James Don Powell
Farshad Rajabipour
Kare Reknes
Andres Salas
Andrea J. Schokker
Tim James Smith
Michael D. A. Thomas

James R. Van Acker
Thomas J. Van Dam*
Olafur H. Wallevik
David Wan
Vicky Zajakowski

*Subcommittee Co-chair

Consulting Members

Cesar A. Constantino

John D. Hull

Martha G. VanGeem

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 mate-

rials 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.

ACI Committee Reports, Guides, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

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

ACI 130R-19 was adopted and published January 2019.

Copyright © 2019, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

CONTENTS

CHAPTER 1—INTRODUCTION AND SCOPE, p. 2

- 1.1—Introduction, p. 2
- 1.2—Scope, p. 3

CHAPTER 2—DEFINITIONS, p. 3**CHAPTER 3—CEMENTITIOUS MATERIALS, p. 3**

- 3.1—Portland cement, p. 3
- 3.2—Blended hydraulic cement, p. 6
- 3.3—Supplementary cementitious materials, p. 9
- 3.4—Non-portland cement binders, p. 11

CHAPTER 4—AGGREGATES AND FILLERS, p. 14

- 4.1—Introduction, p. 14
- 4.2—Natural sand and gravel, p. 14
- 4.3—Crushed stone, p. 15
- 4.4—Lightweight aggregates, p. 16
- 4.5—Recycled/reused aggregates, p. 16
- 4.6—Mineral filler, p. 19

CHAPTER 5—CHEMICAL ADMIXTURES AND ADDITIVES, p. 19

- 5.1—Overview, p. 19
- 5.2—Materials used in admixture formulations, p. 20
- 5.3—Environmental impact, p. 20
- 5.4—Sustainable benefits of chemical admixtures, p. 21
- 5.5—Reducing concrete waste, p. 23

CHAPTER 6—WATER, p. 23

- 6.1—Overview, p. 23
- 6.2—Standards for water in concrete mixtures, p. 23
- 6.3—Strategies for reducing consumption of potable water in production of concrete, p. 24
- 6.4—Summary, p. 25

CHAPTER 7—REINFORCEMENT, p. 25

- 7.1—Introduction, p. 25
- 7.2—Steel reinforcement, p. 26
- 7.3—Steel reinforcing bars, p. 26
- 7.4—Welded-wire reinforcement, p. 26
- 7.5—Fiber reinforcement, p. 27
- 7.6—Nonferrous reinforcement, p. 27

CHAPTER 8—CONCLUSION, p. 28**CHAPTER 9—REFERENCES, p. 28**

- Authored documents, p. 29

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

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

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

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

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

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

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

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

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

1.2—Scope

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

CHAPTER 2—DEFINITIONS

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

CHAPTER 3—CEMENTITIOUS MATERIALS

3.1—Portland cement

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

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

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

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

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

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

Although CO₂ makes up a significant portion in GHG emissions, other compounds such as methane (CH₄) and nitrous oxide (N₂O) are also considered in assessing environmental impacts of a material. The combined impact of GHG emissions is commonly referred to as CO₂ equivalents, or CO₂e. CO₂e is a measurement used to normalize the emissions from various greenhouse gases based on their global warming potential (GWP). CO₂e are commonly expressed as terragrams of carbon dioxide equivalents (a terragram is 1 million metric tons). The CO₂e for a gas is derived by multiplying the tons of the gas by its associated GWP, thus: TgCO₂e = (Gg of gas) × (GWP) × (Tg/1000Gg). (Environmental Protection Agency 2012). For example, the GWP of CH₄ is 24; that is, the impact of unit mass of CH₄ may have a similar impact on global warming over 100 years as 24 units mass of CO₂.

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