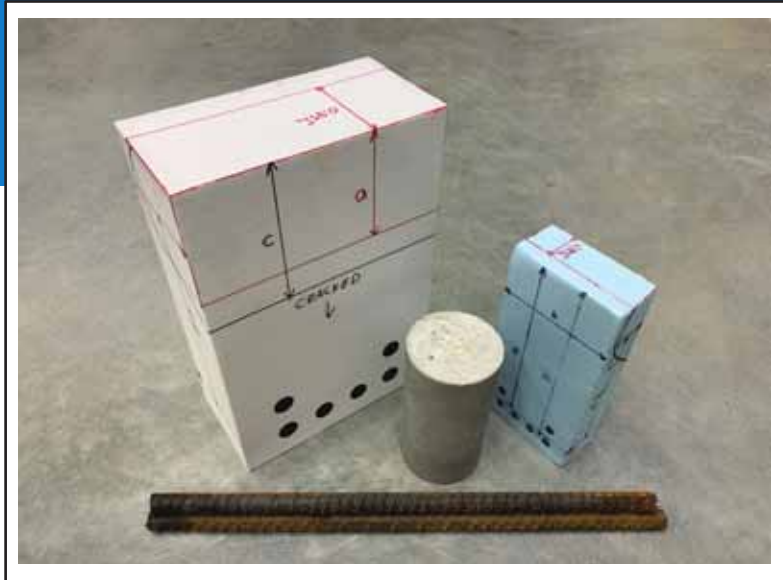


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SYMPOSIUM VOLUME



Best Practices and Lessons Learned for
Teaching Concrete Materials and
Reinforced Concrete

SP-359

Editors:
Benjamin Z. Dymond and J. Chris Carroll



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Best Practices and Lessons Learned for Teaching Concrete Materials and Reinforced Concrete

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October 17-21, 2021

Editors:
Benjamin Z. Dymond
and J. Chris Carroll



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Best Practices and Lessons Learned for Teaching Concrete Materials and Reinforced Concrete

The manuscripts included herein introduce common learning theories and methods in engineering education that can be specifically applied to the topics of reinforced concrete and concrete materials. The papers focus on the application of these theories to specific concrete-related topics and suggest ways to implement these methods in university classrooms. The primary goal of this Special Publication is to provide pedagogical resources, ideas, and techniques that can be implemented by anyone that accepts the challenge of teaching reinforced concrete and concrete materials, from a new instructor to an experienced professor.

To disseminate effective teaching methods among a global group of educators and learners, ACI Committee S802 organized two sessions entitled “Best Practices and Lessons Learned for Teaching Concrete Materials and Reinforced Concrete” at the Spring 2021 ACI Virtual Convention. The first session was focused on best practices teaching concrete materials and the second session was focused on best practices teaching introductory reinforced concrete. The manuscripts in this Special Publication are organized in the order in which they were presented at the ACI Convention.

The co-editors, Dr. Benjamin Dymond and Dr. J. Chris Carroll, are grateful for the contributions from the Special Publication authors and sincerely value the time and effort of the authors in preparing the papers in this volume. Furthermore, the Special Publication would not have been possible without the effort expended by the experts who peer reviewed the papers in this volume.

Benjamin Dymond and J. Chris Carroll
Co-Editors

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Effective Teaching Methods in Concrete Education

Matthew K. Swenty, Benjamin Z. Dymond, J. Chris Carroll

Synopsis: Teaching engineering students reinforced concrete and concrete materials topics is not a trivial task. Students learn in a variety of different ways and many professors rely on only a few methods of presenting the material and directing learning. The disconnect can create a struggle in the learning process for all parties involved. This paper introduces several different common teaching styles and methods that have been used in engineering education. The methods are compared and contrasted based on complexity, resources required, and preparation time. Various levels of change are discussed from small incremental adjustments to completely redesigning the course. A series of examples are described to demonstrate a few ways of implementing new teaching ideas into a classroom. Companion papers expand upon this introductory paper and provide in-depth and specific applications to topics common in concrete education. The goal of this special publication is to provide a venue to share teaching ideas and make concrete education more effective, efficient, and enjoyable for everyone.

Keywords: Engineering education, civil engineering, learning styles, teaching methods, active learning, reinforced concrete, concrete materials, teaching examples

INTRODUCTION

Educating engineering students is a challenging proposition for a professor. The material is based on difficult subjects that commonly build upon one another requiring the students to thoroughly understand one topic before proceeding to the next. Many times, students desire to learn simple “plug and chug” style equations, but the reality is they must understand the basis for the methods they use as a design engineer. Ultimately, they will be responsible for the safety of the public. Teaching engineering topics has always been challenging since the inception of engineering programs at the turn of the 20th century (McDaniel 1917).

Professors are very well educated and have a thorough understanding of their subject matter. However, most professors do not have any formal training in education, so they must find ways to convey knowledge and help students learn (Welch & Estes 2005). Some in the profession have noted the importance of transforming the engineering education experience by placing more emphasis on quality teaching (TUEE 2013). Many professors revert to a default, comfortable teaching method or technique that their favorite professors used or a method that is easy to implement. One major issue is making useful and updated material easily accessible for a professor to use in their quest to educate effectively.

Students come from different backgrounds and acquire and remember knowledge, commonly called learning, in a variety of ways. Competing educational theories state that either the approach to learning or the learning style affects student learning. Some believe a student’s approach to learning is influenced by their motivation and their stimulations to learn by outside influences. Others believe that learning styles are attributed to the psychological attributes the student has for processing information. Learning styles tend to remain static for an individual (Cuthbert 2005). Criticism of each theory continues, but many in engineering education, particularly in the United States, rely on the learning styles approach (Cuthbert 2005, Popescu 2009). From the perspective of the learning style, there is a strong likelihood that some students in a class struggle to understand a teacher because of the teaching methods or style, not because of the technical difficulty of the material. Professors must identify this dilemma and target the variety of learning styles and motivations used by their students (Dunn & Griggs 2000; Felder & Silverman 1988).

There are many different methods of presenting information to students and guiding the learning process (Wankat & Oreovicz 2015). It is important that all professors maintain a flexible attitude when practicing the art of teaching. The teaching process changes with time and with students. Even those who have taught for many years must be patient and assess their own teaching methods regularly to help their students learn effectively (Stronge et al. 2004).

OVERVIEW OF THIS SPECIAL PUBLICATION SERIES

This paper is the first in a special publication (SP) series that contains nine additional manuscripts designed to introduce common learning theories and methods in engineering education that can be specifically applied to the topics of reinforced concrete and concrete materials. The companion papers focus on the application of these theories to specific topics, which include:

2. Approaches to Teaching Cement Hydration Processes to Undergraduates
3. Pedagogical Techniques used to Teach Fresh and Hardened Concrete Properties
4. Teaching Additive Manufacturing with Consideration for Cementitious Materials
5. Effective Teaching Methods for Non-destructive Testing Techniques
6. Pedagogical Techniques used to Teach Detailing of Reinforced Concrete Structures
7. Teaching the Equivalent Rectangular Stress Block
8. Teaching Flexural Strength Failure Modes in Reinforced Concrete I
9. Active and Visual Methods for Teaching Nonrectangular Reinforced Concrete Beams
10. Approaches for Teaching Shear Analysis and Design of Reinforced Concrete

Included herein are suggested ways to implement these methods, a list of time commitments for each method, and a description of their complexity. The primary goal of this special publication is to provide pedagogical resources, ideas, and techniques that can be implemented by anyone that accepts the challenge of teaching reinforced concrete and concrete materials, from a new instructor to an experienced professor.

BACKGROUND

Pedagogy is commonly defined as the practice and method of teaching a subject. This pedagogical study of concrete topics is designed to help professors expand their repertoire of methods and reach students with a myriad of learning styles. Within this context, constructivism is the process by which students build new knowledge upon previous knowledge (Michael 2006). The professor is tasked with guiding this process with either minimum intervention, significant assistance, or some other measured amount of involvement (Kirschner et al. 2006). One challenge is that students enter a course with varying levels of base knowledge and assumptions about the topics. When deciding how much guidance to give, a professor must be aware of these limitations (Brown et al. 2018; Van Wie et al. 2012). Another challenge is that professors tend to assume that the concepts and problems are easy. Many students disagree with this assumption, creating further confusion between the professor and students in the learning process.

Part of the students' assumptions when entering the class are based on their epistemic beliefs and motivation. The challenge for the professor is to not only teach the material to students, but to instill a desire to learn the subject. Considering how problems are framed and the way the homework is presented in class can help (Faber & Benson 2017). Inspiring students is still a very difficult task, but it can be accomplished through various teaching methods.

Traditional teaching methods can be used effectively to inspire students, but research has shown that every student learns differently. Engineers are typically sensory and visual learners, but may also be inductive, active, or even global learners (Dunn & Griggs 2000; DeMonbrun et al. 2017; Behrouzi 2016; Newson & Delatte 2011). While most students fit into one of these categories, any given classroom may contain all types of learners. There is no standard way of learning that works for everyone. One of the most obvious outliers in a classroom may be the professor. Professors have been documented to learn differently than their students; hence, the learning styles they select for instruction do not always align well with the needs of the students (Carroll et al. 2019). An effective professor will recognize this and adjust. Most students respect professors who try new methods and the students frequently enjoy the variety (Stronge et al. 2004). The professor must stay attuned to the class and recognize adjustments in teaching methods may be needed.

TEACHING METHODS

Traditional methods

Lectures are a common form of passive learning because students receive the information as it is spoken to them (Prince 2004; Newson & Delatte 2011). The students are not required to think about, act on, or use the knowledge that is set before them. Typically, students do not achieve higher order cognitive levels by listening and taking notes from lectures (Derting & Ebert-May 2010) and the lecturing style of teaching is widely overused (Wankat & Oreovicz 2015). Another common application of the lecture format is called deductive learning. Deductive learning methods constitute the situation when esoteric theories are first presented in a lecture followed by examples that apply the theories (Prince & Felder 2006). Deductive methods are highly structured lectures that are predictable and orderly (Newson & Delatte 2011). Deductive learning does have value and is widely used in engineering classrooms.

Alternatively, the premise of inductive learning is people are more interested in learning a topic if they first see the need to solve a related problem (Prince & Felder 2006). A case study, observation, or dilemma can be used to make students think about the problem and gain interest in finding a solution (Prince & Felder 2006). Once a person sees a real-world problem or phenomena they become more interested in learning about the situation. In many ways, this is like a Socratic method, where students are asked a question about a phenomenon and then the process is further explained (McDaniel 1917).

There is not universal agreement that courses should be entirely set up with all inductive or deductive teaching methods, even though inductive methods are often promoted (ASCE 2019; Estes et al. 2005). A balance is needed, especially in situations when students first must master a complete set of material (Prince & Felder, 2006). There are distinct bodies of knowledge, some that have been explicitly defined, that must be mastered in engineering (BOK 2019; ABET 2019). While inductive learning can be used effectively, deductive methods have been historically used because of the efficiency in presenting topics. Explaining topics or using inductive learning is very difficult if students do not have the required base knowledge. Ultimately, students need to know how to solve problems, but they first must master the facts that govern the natural phenomena that drive the solutions (Michael 2006). Inductive

methods show great gains in student understanding, but deductive methods are still used appropriately and effectively in many class settings.

Active learning methods

Active learning is a term used to describe instructional activities that engage students in the learning process (Prince 2004). There are many types of teaching methods and styles that are categorized as active. Active learning is not a new technique; some of these methods have existed for over 200 years (Wankat & Oreovicz 2015). The premise is to engage students, so they reflect and use the ideas, which leads to better retention, thinking skills, discovery of knowledge, and interest in the material (Michael 2006; Bhatia & Chen 2015; Cleary 2006). Students tend to learn more, and the failure rate declines (Nguyen et al. 2016). Active methods are frequently used as inductive teaching methods although there are applications for adding short active learning methods in a deductive teaching lecture (Prince & Felder 2006). Simple active methods can be used for a few minutes within a class to help setup the objectives at the beginning of class, emphasize a point within a course, or conclude a lecture (Carroll 2013). Some of the more common and simple active teaching methods that have been shown to be effective in an engineering classroom are in Table 1.

Table 1—Common and Simple Active Learning Techniques

Methods	Description	Complexity*
Think-Pair-Share (TPS)	Students think about a concept, pair up to exchange thoughts, and share with a larger group. (Stronge et al. 2004)	Simple, 5 minutes or more, Sharing must be organized to keep the class on task.
Peer Discussion (PD)	Students explain topics to one another, share notes, and/or ask each other questions. (Michael 2006; Wankat & Oreovicz 2015)	Simple, 5 minutes or less
Interactive Quizzes (IQ)	Create a competition by breaking the students into groups. Ask the groups questions and measure their accuracy and quickness to respond. (Wankat & Oreovicz 2015)	Simple/intermediate, 5 minutes or more, Requires preparation of specific questions.
Minute Paper (MinP)	Students have one minute to organize their thoughts related to the day's topics and rank the major points concisely. Students may add their own question at the end to make the assessment interactive. (Angelo & Cross 1993)	Simple, 5 minutes or less at the end of class, May require the review of the submittals.
Muddiest Point (MudP)	Students write a rapid response to one question: "What was the muddiest point in the lecture (discussion, homework assignment, etc.)?" Muddiest means most unclear or most confusing.	Simple, 5 minutes or less, Requires review of the results.
Skeleton Style Notes (SSN)	Note handouts are created without key concepts or without key steps in the example problems. Students must listen to lectures and fill in the missing information. (Dymond et al. 2019)	Simple-complex, 5 minutes to a full class, The creation of the notes takes significant time, but implementation is easy.
Field Trips (FT)	Take students on a short walk to a structure or application near the classroom that demonstrates the relevant topic. (Wankat & Oreovicz 2015)	Simple-intermediate, 10 minutes or more, Could be a simple local walking tour or more complex off-site tour.
Physical Artifacts (PA)	Provide a physical representation or model that can be visualized and explored in class. (Behrouzi 2016)	Simple-complex, 5 minutes or less, Can require differing levels of time to prepare the artifact.

*The difficulty scale is simple/intermediate/complex, the time is an estimate of how long the activity will take in class, and the note includes any caveats or special preparations.

Most simple methods can be used sparingly or on a regular basis depending on the discretion and needs of the professor. A benefit of using them sparingly is they do not require major changes to the teaching style or course schedule. For a professor who has never tried any form of active teaching, many of these methods are easier to implement, require little additional resources, and do not take a lot of time. For example, think-pair-share is a method that can be implemented for a few minutes in class after presenting an important concept. Each student individually ponders the concepts and pairs up with another student to discuss what they learned. Next, the pair

shares their main concepts and questions with a larger group. The concept can be implemented in about five minutes and works well in smaller classes. While the method could be used for one or more lectures, students have shown that with repetitive use, they become more comfortable and willing to share (Stronge et al. 2004). Peer discussion is like think-pair-share but requires less time and works in any size class. Students are given a few minutes after a concept is presented to compare their notes and explain the concepts to one another (Michael 2006; Wankat & Oreovicz 2015). Many students learn better in a group setting, which can lead to better thinking skills, further study, and improved retention in the class (Prince 2004). A more complex version is to use interactive quizzes or “game show” style questions; the students break up into small groups and the professor presents questions for them to answer. Technology such as clickers or smartphone apps may be used but are not required. Students can raise their hand or alternate between groups like a trivia game as they answer the questions (Wankat & Oreovicz 2015). This method may take more preparation from the professor to prepare good questions, but it also simulates quiz or test assessments in a fun, enjoyable manner.

Two other methods, the minute paper and muddiest point, help the students think about their learning and give feedback to the professor. With the minute paper, the students are asked to take one minute at the conclusion of a class to reflect on the key topics of the day. The professor can also ask an additional specific question for the students to answer in their minute paper to make the activity more interactive. An even easier, but similar method is called muddiest point. At some point during the lecture, students are asked to write down a concept that is most unclear or “muddy.” The professor can collect their written ideas or take a vote to gather feedback. This allows both sides to interact in the learning process and take time to revisit or clarify topics that are difficult to understand.

A simple technique of adding some variety to a deductive teaching style is to use skeleton style notes. The professor makes a master set of notes that includes the key concepts and example problems. However, the students receive incomplete notes with most of the information and key steps left out (Dymond et al. 2020). In class the students are led through the notes with some form of guidance. This can be as simple as guiding them with step-by-step instruction from the beginning to end or as complex as challenging them to solve the example problems on their own. Presenting material in this style allows extreme flexibility for the professor and a very organized framework for the student. The downside is creating the notes for the first time is very time consuming.

Many students are visual learners and make gains when they physically see a concept. Two visual learning methods are field trips and the use of physical artifacts in the classroom. Field trips are a way to show a unique image that cannot be transported into a classroom. Many college campuses have excellent examples of reinforced concrete in their buildings, on their grounds, and as part of their transportation systems. While it may take a few minutes to go on a walk, moving to a different environment and visualizing applications can be extremely helpful to student understanding and retention of the topic (Wankat & Oreovicz 2015). A more flexible and independent style of field trip is to ask the students to complete a scavenger hunt and find examples of concepts from class. This does not need to be complicated and can be done individually or within a group (Swenty et al. 2016). More complex trips to construction sites or other locations such as a precast concrete plant are useful, but they are normally time consuming and may be difficult to implement in a class. When field trips cannot be used, physical artifacts are another excellent way to help students visualize concepts in the classroom. The American Society of Civil Engineers (ASCE) ExCEED model for civil engineering instruction promotes having a physical model whenever possible (Welch & Estes 2005). There are different sizes and styles of models that vary in complexity and time commitment (Vander Schaaf & Klosky 2003). Examples of smaller models include using pieces of Styrofoam or 2x4 lumber to recreate the rectangular stress block for a reinforced concrete beam (Carroll et al. 2021). Many engineering students tend to be visual and sensory learners, which explains why artifacts can be so effective (Behrouzi 2016). In addition, physical models can help identify misconceptions and improve understanding (Van Wie et al. 2012).

While many simple active learning methods are good additions to a class, there are more advanced active learning techniques that have also been shown to be very effective. These methods require more preparation and are significantly different than traditional methods of instruction. Care must be taken when considering one of these methods because of the significant changes and effort required on the part of the professor. A summary of some common advanced teaching techniques is shown in Table 2.

Table 2—Advanced Active Learning Techniques

Methods	Description	Complexity*
Collaborative Learning (CoL)	Problems are created for small groups to solve in or out of class. They may vary in complexity and time commitment. (Prince 2004; Derting & Ebert-May 2010)	Intermediate/very complex, 10 minutes or more, Can vary greatly depending on if it is an in-class problem or semester project.
Cooperative Learning (CoopL)	Problems are created for small groups to solve in or out of class, but grades are typically assigned to everyone separately. (Prince 2004; Wankat & Oreovicz 2015)	Intermediate/very complex, 10 minutes or more, Can vary greatly depending on the size of the project and the grading/assessment methods.
Discussion Learning (DL)	Requires coordinated prompts, the professor's guidance, and students with base knowledge of the topic. (Wankat & Oreovicz 2015)	Intermediate/complex, 5 minutes or more, Creating discussion topics and keeping the class focused is important; This can be difficult with large classes. The method is not as effective for transferring new facts, but good for relating and applying knowledge.
Inquiry-based Learning (IBL)	A broad method that presents a question or task that challenges students to search for a solution. IBL encompasses many other methods including ProbBL, ProjBL, SL, and CBL. (Aditomo et al. 2013; Berger 2016; Derting & Ebert-May 2010; Dewoolkar et al. 2009; Prince & Felder 2006)	Intermediate-very complex, One class or more, Creating problems, projects, cases, and questions can take substantial amounts of time. The methods for IBL vary significantly, but all promote curiosity in the student.
Problem-based Learning (ProbBL)	Must write open-ended contextual problems to solve. Professors facilitate learning and knowledge acquisition through the problem-solving process. (Rumsey et al. 2010; Roiter 2015; Roiter 2009; Prince & Felder 2006; Prince 2004; Wankat & Oreovicz 2015)	Very complex, One class or more, A very challenging method to implement because it is difficult for students and professors. Good for long-term, but not short-term knowledge acquisition.
Project-based Learning (ProjBL)	An open-ended project with multiple tasks is presented. Students complete the tasks based on the knowledge they already have. (Wankat & Oreovicz 2015; Prince & Felder 2006)	Complex, Multiple classes, It is challenging to implement because it takes oversight and significant time to complete. The benefits are a deeper understanding and a better connection to their knowledge base.
Service Learning (SL)	While similar to project-based learning, the solution is implemented for a real-world problem. (Wankat & Oreovicz 2015)	Very complex, Multiple classes, The method has the same challenges and benefits as project-based learning. Additionally, communication skills are improved, the process has an element of accountability to clients, and the results are very rewarding.
Case-Based Learning (CBL)	Cases relevant to the class objectives are identified or developed. The professor integrates the case into the lecture or class discussion (Delatte 2012; Bhatia & Chen 2015; Newson & Delatte 2011; Wankat & Oreovicz 2015; Prince & Felder 2006)	Intermediate-very complex, 5 minutes (case histories) up to multiple classes (case studies), Identifying cases takes background work. Case histories are normally easier to present than coordinating class discussions for case studies.
Just-in-Time Learning (JITL)	Requires the professor to assign pre-class work, assess gains from this work, and adjust class material immediately prior to a lecture. (Prince & Felder 2006)	Very complex, No additional class time or significant out of class time for students and professors. Requires very careful coordination of the class.

*The difficulty scale is simple/intermediate/complex, the time is an estimate of how long the activity will take in class, and the note includes any caveats or special preparations.

Table 2 (cont.)—Advanced Active Learning Techniques

Methods	Description	Complexity*
Experiential Learning (EL)	Requires the construction and/or testing of physical samples. This may require additional out of class activities and lab resources. (Cleary 2006; Roberts & Thompson 2005; Carroll et al. 2020; Dymond et al. 2020)	Intermediate-very complex, 15 minutes to multiple classes, Testing samples can be relatively easy to implement. When involving students in the design, construction, and testing setup, the process is much more complex.
Flipped Classroom (FCL)	The class is organized with significant pre-class work for the students including pre-assessments. In class exercises are focused on solving example problems together and clarifying concepts. (Wankat & Oreovicz 2015)	Very complex, One or more classes, The presentation of material outside of class takes significant time to organize on a course management system or other distribution platform. This requires disciplined students and excellent communication between all parties.
Entrepreneurially-Minded Learning (EML)	Requires the professor to make class presentations and problems that force students to search for design alternatives and create value for a project owner. Many times, this is used in conjunction with ProbBL and ProjBL. (Gerhart & Melton 2016; Melton 2019; The Kern Family Foundation 2021)	Complex – very complex, One class or more, The class requires careful coordination of in class presentations and assignments framed with an entrepreneurial focus.
Culturally-Responsive Learning (CRL)	The topics in the course are presented from a cultural perspective with respect to such items as diverse populations, politics, and environmental concerns. The premise is engineering topics are not taught in a vacuum and the context in how they are presented is important. (Paris 2012; Canney & Bielefeldt 2015; Brockbank & McGill 2007; Castaneda & Mejia 2018; Richards et al. 2007; Grimberg & Gummer 2012)	Intermediate-very complex One or more classes, The learning process includes references, examples, and/or problems with cultural topics and context. This can be used in conjunction with other teaching styles, but the course material may require significant adjustments.

*The difficulty scale is simple/intermediate/complex, the time is an estimate of how long the activity will take in class, and the note includes any caveats or special preparations.

Collaborative and cooperative learning promotes the interaction of students during the learning process. In collaborative learning, small groups are formed that work on a common task as a team. The tasks could be as simple as working example problems or performing an experiment in small groups or more complex like solving a semester long design problem (Wankat & Oreovicz 2015). The benefits of forming small groups are the discussion that ensues, which promotes further study, thinking skills, and positive attitudes toward the class. The result is better retention in the class and higher grades (Prince 2004). Collaborative work is commonly used in conjunction with other advanced methods of instruction (Derting & Ebert-May 2010). Cooperative learning is like collaborative learning except the students receive an independent grade from the assigned work in cooperative learning, while grades are typically assigned to the group in collaborative learning. Similar results have been observed from cooperative learning and collaborative learning, such as improved relationship building skills, better student attitudes, more social support, and boosted confidence (Prince 2004).

A discussion-focused class requires the students to have previously formed a solid base knowledge (e.g., in previous lectures or courses) to properly discuss and contribute to the proposed questions. The students can learn at a higher level of complexity if the questions are properly formed, which also helps the students remember the topics. The professor must guide the conversation to keep it on task. This method is hard to implement effectively with large classes; keeping all the students involved is very challenging (Wankat & Oreovicz 2015).

Inquiry-based learning is a category of student-centered learning that includes problem-based learning, project-based learning, service learning, and case-based studies (Aditomo et al. 2013). The overarching goal is to help students learn the process of independent discovery by presenting problems and challenging them to ask questions (Berger 2016, Derting & Ebert-May 2010). Students learn how to solve problems and new concepts in the process. Significant gains have been shown in analytic ability, process skills, student perception, and academic achievement

(Prince & Felder 2006). The methods vary significantly and can be project based, physical models, or laboratory focused (Dewoolkar et al. 2009).

Problem-based learning focuses on knowledge acquisition (Wankat & Oreovicz 2015). With this method, a problem is presented to the students within appropriate context, but the questions are open-ended and require the professor to serve as a facilitator. The method is extremely challenging to both the student and professor to implement, and many students do not like it at first. The short-term knowledge gains are less than other methods, but the long-term retention and study habits are significant. Students begin to embrace the method once they go through the process for the first time (Prince & Felder 2006). The method can be used to help build communication and team skills but may sacrifice independence and critical thinking. Some prefer to use problem-based learning sparingly rather than universally (Roiter 2009; 2015).

Project-based learning is focused on the application of previously learned knowledge and is an advanced method of teaching (Wankat & Oreovicz 2015). While the name is very similar to problem-based learning, the result is different. In project-based learning, students are taking previously learned knowledge and making connections among the concepts and obtaining higher order learning. Most projects are open-ended and require multiple tasks to complete. The result can be improved conceptual understanding, an ability to solve open-ended problems, and confidence in solving problems. A good application is in a design or capstone style course (Prince & Felder 2006; Dymond & Swenty 2017; Swenty et al. 2019).

Service learning is a type of project-based learning where the results are implemented in the real world. The benefit of using this approach is the realistic nature of the project and accountability to the client. Communication, teamwork, and time management skills are improved. The courses can be very labor intensive, require significant professor oversight, and demand accountability; however, the results are extremely rewarding (Wankat & Oreovicz 2015).

Case-based teaching can be divided into two similar methods called case histories and case studies. In both situations, historical or hypothetical situations relevant to the topics in class are presented to the students. Case histories are based on a lecture-style format, while case studies are a discussion style format (Newson & Delatte 2011). Many times, these methods can be implemented with the help of practitioners because of their practical knowledge and experience (Wankat & Oreovicz 2015). Both successful cases and failure cases may be used depending on the preference of the professor and the specific topic (Delatte 2012). Case studies can be presented to groups or individual students who are then required to solve the problem or address the situation. The results include improved student retention, problem-solving skills, and application of the material, in addition to better communication and decision-making skills (Prince & Felder 2006). The process of reflection, whether in a case study or other format, has been shown to improve long-term knowledge retention (Jordi 2011). The National Academy of Engineering (NAE) supports this teaching method (Bhatia & Chen 2015)

Just-in-time teaching is an interactive method of teaching based on feedback given prior to the class. Students perform work in preparation for class, then provide some form of feedback to the professor. Feedback can be supplied in a discussion forum, quiz, or other form of assessment. Online course management systems are helpful for gathering and organizing feedback. The professor gathers the feedback and adjusts the class material based on the results. This method forces more interaction and helps tailor the material to the student population. Like other interactive teaching methods, Prince and Felder (2006) reported that students make gains in knowledge retention, but the method requires careful preparation immediately prior to the class.

Experiential learning has been an important part of engineering education through laboratory exercises and in-class demonstrations. Providing hands-on, physical activities is known to be very helpful to student understanding and visualization (Cleary 2006; Behrouzi 2016). This is especially true in engineering courses like reinforced concrete that involve design and construction. Experiences can be simple or extremely complex depending on the topic and time permitted. Students can be involved in the construction and testing of small or large specimens (Dymond et al. 2020). The construction processes help students visualize cross sections, integrate composite shapes, and see detailing requirements. Testing samples helps with the visualization of failure modes, forensics, ductility, and serviceability, but the key to experiential learning is providing students with an opportunity to reflect on the activities (Carroll et al. 2020). One of the positive results is better engagement in the class and with the material

(Roberts & Thompson 2005). Students tend to remember the topics from the activities better in the long term. Depending on the scale, experiential learning can require significant amounts of preparation and resources.

A flipped classroom learning environment includes reorganizing the classes to focus on solving problems and answering questions based on pre-class assignments. The students are required to complete readings, study posted material, and/or watch videos on the topics that will be covered in a class. They are typically given an assessment before class to ensure they are prepared. Online course management systems are routinely used to implement the pre-assignments and assessments. The professor focusses on answering questions in class and working with the students on example problems rather than teaching them the material in a deductive manner. Flipped classrooms require significant changes to most professor's teaching styles and are disliked by some professors and students. The effectiveness is also dependent on the situation and persons involved (Wankat & Oreovicz 2015).

Entrepreneurially-minded learning is a method used to challenge students to go beyond learning skills and think about how to use those skills to make connections and create value (Melton 2019; The Kern Family Foundation 2021). Students must approach problems from a broader perspective and think in terms of a project owner. Entrepreneurial-minded learning pushes the students to use their curiosity to discover design alternates that may not be conventional (Gerhart & Melton 2016). The method is routinely used in conjunction with other methods such as project-based learning or problem-based learning. The method challenges the professor to create open-ended assignments that allow students to use their creativity. Class instruction must also force the students to question the standard processes and design solutions and create additional options.

Culturally-responsive learning is a method built on the assumption that learning is a social process and the context and conditions in which learning takes place are important (Brockbank & McGill 2007). Professors should recognize that engineering is not performed in a vacuum and engineers solve problems within a world that has social, environmental, political, and civic influences (Canney & Bielefeldt 2015; Paris 2012). Students come from varying backgrounds and life experiences that should be connected to classroom instruction (Castaneda & Mejia 2018; Richards et al. 2007). An education system developed for culturally-responsive student learning must support the diversity of the student population and the world they will graduate into (Grimberg & Gummer 2012). Many other teaching methods can be adapted for use with a culturally-responsive learning focus.

TEACHING EXAMPLES

As discussed, there are a host of different teaching methods and styles. The following list of examples has been used in engineering courses through implementation of many of the previously described methods. Some of these examples use multiple active learning techniques. This is not a comprehensive list, but it is meant to provide some context to help explain many of the methods discussed in this paper. The companion papers in this special publication series continue to focus on the application of these teaching methods and styles to specific topics that are common in introductory reinforced concrete and concrete materials courses.

Simple examples – implemented in part of a class

With many classes lasting an hour or longer in length, a common practice is to insert some form of break every 15 to 20 minutes. These breaks do not need to necessarily change the subject or lose focus, but the breaks allow students to reinforce the concept just presented and change pace from the typical teaching format. For instance, when discussing stirrups in reinforced concrete, a brief picture showing a local construction site with reinforcing bar cages or a video describing the construction process emphasizes the concept and breaks up the presentation. Another example is to take a three-minute pause, have the students break into small groups, and then discuss if they understand how a stirrup is placed in a reinforced concrete beam (Wankat & Oreovicz 2015). Students can explain the concept to each other and then ask the professor if there is a question that none of them understand. Any type of short break during a longer lecture class can help students reflect on what they are learning and refocus for the next part of class (Prince 2004).

Another method that requires a large initial time investment are skeleton style notes; however, they are easy to implement. Creating handouts that guide the students can make note taking more efficient and provide structure for group work (Dymond et al. 2019). For example, when looking at load paths, the plan view of the structure can be provided with labels of the column lines. This provides a very clear layout that everyone can build upon during the lecture. Students can focus on the key concepts while drawings, pictures, and tables can be inserted into the notes

efficiently. This prevents students from having to copy mundane information, highlights the most important topics, provides a systematic outline for note taking, and allows more time to work in small groups or perform similar active learning tasks.

A similar method to skeleton notes is to use interactive programs to show design iterations and options (Das 2008; Wenzel 1987; Urgessa 2014). For example, a Mathcad file can be created to compute the nominal capacity of a concrete beam. Variables that are common to all beams such as width or area of steel can be changed and then the capacity is instantaneously computed. Students can plot the results in real time to visualize patterns in the capacity as variables are changed. They can do this with their personal computing device in class or the professor can demonstrate the process on screen. Preparing these types of files is relatively simple.

Physical models are a simple method that provide an actual sample that is seen and even handled in class. An example is to create a Styrofoam or wooden 2x4 block to illustrate the equivalent rectangular concrete stress block (Carroll et al. 2021). This could be expanded to create a building made of Styrofoam and balsa wood to demonstrate slab design. Another option is to create a clear acrylic beam with colored dowels inside representing a fully-detailed concrete beam (Behrouzi 2016). Understandably, the initial investment takes time and resources, but the use of these models in class is straightforward.

A good technique to use for reviewing material, particularly before a test or quiz, is competitive learning. Students enjoy breaking into groups and quizzing one another or competing in a quiz show style format (Wankat & Oreovicz 2015). For example, students can form groups of three to five people, the professor can ask a question, and the groups can submit their answers to the class within 30 seconds. A tally of correct answers for each group is tabulated. This form of review helps increase student retention and adds a fun twist to the course. Implementing this method is not difficult. The professor can use homework or short answer style questions that may have already been asked or are common on the fundamentals of engineering (FE) exam.

Intermediate examples – implemented in a class

A method that takes some coordination is the use of outside experts. This can be done by having a guest speaker visit the class to share their experiences and show visuals of their work. For example, a design engineer can come show construction drawings and then pictures of their recent projects. A more advanced technique is to prepare the speaker ahead of time to discuss specific decisions they had to make on a project. A prompted communicator can describe their experience in innovation, ethics, and judgement when using concrete, which are topics that are difficult to teach or acquire while in school (Hanson & Brophy 2012). Using remote video capabilities or prerecorded addresses are possible ways to achieve the same effect if a guest speaker cannot attend the class or a professor wants to focus on a specific topic.

Adding a case history to a lecture can be a relatively straight forward way to demonstrate a concept in reinforced concrete. For example, two failure case histories, the Murrah Building in Oklahoma City and the Pentagon in Virginia, demonstrate different failure modes and progressive collapse of reinforced concrete. Other examples include the Harbor Cay Condominium failure or the Air Force Warehouse failures (Roberts & Thompson 2005; Delatte 2012). These examples can briefly highlight important topics such as detailing or the development of punching shear equations. Other applications can include expanding these same case histories into case studies. Case studies involve a more in-depth discussion about the ethics, professionalism, and broader societal impacts of these concrete structures. Students are given assignments to write an in-depth analysis or make a presentation about the topic, reflect on the case, and evaluate the experience.

Advanced examples – implemented in multiple classes

Experiential learning is a more complex method of teaching, but it is generally enjoyed by students and helpful for long-term cognitive memory. Numerous examples have been used in reinforced concrete courses including the design, construction, and testing of reinforced concrete beams. Reports have stated that the students enjoy this method of teaching and retain knowledge from the experience (Cleary 2006; Rumsey et al. 2010; Roberts & Thompson 2005; Dymond et al. 2020). A variation of this approach is to implement competitions into the curriculum, which can include the design and testing of a specimen to meet predetermined strength, deflection, or cost criteria. Students tend to enjoy comparing their results to one another and embrace the concepts in the design process (Roberts & Thompson 2005; Phillips et al. 2018; Carroll 2013).

An advanced example of implementing field trips and experiential learning is to use an extended travel experience to highlight construction, design, and unique uses of reinforced concrete. When living out an experience and seeing examples firsthand, learning is more in depth and collaborations are deeper (McClellan & Hyle 2012). Examples of this could be as simple as an extended day trip to see construction sites in a nearby city or as complex as an international trip to London to contrast historical Roman structures with modern uses of concrete. A unique example is to hold class in or at a construction site, where explaining design concepts is easy to do in person (Swan 2006).

A course-long, problem-based learning project can be assigned to students where they are responsible for building a computer program that performs the basic steps to design a reinforced concrete beam (Rumsey et al. 2010). As previously mentioned, part of this can be demonstrated in class by changing design parameters, but making the exercise an assigned project involves the students in a deeper way. They are required to create the program, check their calculations, and communicate the results. Software such as Mathcad or Excel can be used as the platform and group learning can help individuals understand the complexity of the project and provide an opportunity to reflect on the process.

Project-based learning is one of the most advanced teaching methods and requires significant time and organization. Phillips et al. (2018) implemented an example of this when a class converted two days into a bridge problem-solving event. The students were required to design, build, and test a bridge structure to demonstrate mechanics principles while competing against other teams for the most efficient design. The students added a learning-by-failure component to this project when they compared how the design of each group failed. This method could also be implemented outside of class or span weeks of time; regardless, it is an advanced and challenging method.

Teaching with a flipped classroom requires a significant change to the infrastructure of most classes, especially the work required outside of class. Al Jassmi et al. (2019) converted an entire course into a series of short video lectures and reading assignments that were hosted in an online course management system. The students were required to do work before class and take an assessment quiz to ensure they had completed the work. The professor used normal class times to work example problems, answer student's questions, and assign projects. The results have shown that students have better grades, but some students still need explanation of the concepts, even after the pre-assignments.

LESSONS LEARNED

The previous sections described many traditional and active learning methods and included a selection of examples. Many of the teaching methods have mixed results depending on the course, student population, and implementation. Some students reject a method or are slow to accept the change in presentation style (Nguyen et al. 2016). Professors should use careful consideration when selecting and implementing one or more methods. In most scenarios, starting with small adjustments and consistently assessing the effectiveness after each incremental change is important. There is no method that will work equally well in all situations.

Lesson preparation with many of these methods takes a time investment and subsequent implementation requires patience. For most professors, teaching is a process that evolves as students change and new methods become accessible. It is not recommended to completely convert a course to a difficult learning style all at once. For example, problem-based learning is not recommended for someone just learning how to teach and is not recommended as the sole teaching method for an entire course (Prince & Felder 2006). Trying a method on one lecture or possibly one learning objective is a good start. After implementation, a professor should determine its effectiveness through student surveys and assessment results. Reflection and changes may be needed, but this should not detract a professor from trying a new method in class.

All professors must keep in mind that there is a distinct body of knowledge that is required in engineering at the undergraduate level (ABET 2019; BOK 2019). Covering all the course content is necessary for future employment, graduate education, and standardized tests (Nguyen et al. 2016). Due to time restrictions and a need for base knowledge, some traditional deductive teaching may be necessary and is likely appropriate. Inserting shorter active methods into more traditional teaching methods is effective (Prince & Felder, 2006). This still allows progression through topics in a class while giving the students active exercises to help clarify and guide the presentation of key concepts. Because of the hierarchical nature of constructivism in the learning process, a professor must be careful to cover the critical body of knowledge completely and effectively.

Many of the teaching methods discussed herein assume that the students already have a base knowledge from physics, statics, materials, and mechanics courses they can use to “construct” additional knowledge. Occasionally students enter engineering courses with incomplete or poor foundational knowledge. They need explicit instruction on what they are learning and how to apply this new content. Using a guided or more traditional lecture style, where example problems are discussed and worked correctly, may be more appropriate for some topics than an unguided method of learning (Kirschner et al. 2006). A professor needs to recognize when an active teaching and learning method may not be effective. This takes experience and an understanding of the engineering program’s required courses, course sequence, and students’ abilities. (Michael 2006; Kong et al. 2017; Brown et al. 2018).

When deciding on a teaching method to implement, it is important to realize that teaching is an art with many good approaches. The correct approach may vary between classes and change with time. The objective is to make changes deliberately and continually check their effectiveness. Teachers should keep an open mind and always clearly communicate the material and expectations with the students regardless of the method selected.

CONCLUSIONS AND RECOMMENDATIONS

This paper described a series of methods for teaching engineering topics including reinforced concrete and concrete materials. Each method was explained in the context of its complexity, time commitment, and preparation. A list of references is provided that describes the methods in more detail. Ultimately, there are many good choices that can be tailored to a professor’s class, teaching experience, resources, and style.

The subsequent papers in this special publication series will demonstrate how many of these teaching methods can be applied to different areas of reinforced concrete and concrete materials. The goal is for educators to review their classroom techniques, reflect on ways to improve, and try new teaching styles to help students learn concrete concepts. Table 3 lists the titles of subsequent papers included in this SP along with the active learning strategies discussed in each.

Table 3—Summary of the Active Learning Strategies included in each Paper in this Special Publication Series

Paper	General Topic	Active Learning Strategies Included																				
		TPS	PD	IQ	MinP	MudP	SSN	FT	PA	CoL	CoopL	DL	IBL	ProbBL	ProjBL	SL	CBL	JITL	EL	FCL	EML	CRL
2	Cement Hydration	X			X	X	X	X	X			X	X	X	X				X			
3	Fresh and Hardened Properties			X											X				X			
4	Additive Manufacturing		X										X	X	X		X		X		X	
5	Non-Destructive Testing								X					X					X			
6	Detailing		X			X	X	X		X			X		X		X		X	X		
7	Equivalent Rectangular Stress Block						X		X				X									
8	Flexural Failure Modes	X	X				X		X			X	X	X			X	X	X			
9	Non-Rectangular Beams						X		X	X				X								
10	Shear Analysis and Design	X	X			X	X		X	X		X		X	X			X	X			

TPS = Think-Pair-Share; PD = Peer Discussion; IQ = Interactive Quizzes; MinP = Minute Paper; MudP = Muddiest Point; SSN = Skeleton-Style Notes; FT = Field Trips; PA = Physical Artifacts; CoL = Collaborative Learning; CoopL = Cooperative Learning; DL = Discussion Learning; IBL = Inquiry-Based Learning; ProbBL = Problem-Based Learning; ProjBL = Project-Based Learning; SL = Service Learning; CBL = Case-Based Learning; JITL = Just-in-Time Learning; EL = Experiential Learning; FCL = Flipped Classroom Learning; EML = Entrepreneurially-Minded Learning; CRP = Culturally-Responsive Learning

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ACI member **Matthew Swenty** is a Professor of Civil and Environmental Engineering at the Virginia Military Institute. He teaches structural engineering and engineering mechanics courses including reinforced concrete design and prestressed concrete. His research interests include novel engineering instructional methods, precast concrete connections, long term bridge assessment, engineering education policies, and applications of ultra-high performance concrete.

ACI member **Ben Dymond** is an Associate Professor in the Department of Civil Engineering, Construction Management, and Environmental Engineering at Northern Arizona University. He is the chair of Committee S802 (Teaching Methods and Materials), secretary of Committee 342 (Bridge Evaluation), and a member of Committees 343 (Bridge Design), 423 (Prestressed), and 123 (Research). His research interests include design and analysis of concrete structural systems and their components, experimental investigations, long-term structural monitoring, and engineering education.

ACI member **J. Chris Carroll** is an Associate Professor and Chair of the Department of Civil, Computer, and Electrical Engineering in the School of Science and Engineering at Saint Louis University. Dr. Carroll has led or assisted with several faculty development workshops to improve engineering education. His research interests are focused on structural engineering education and the behavior of reinforced and prestressed concrete structures.

Approaches to Teaching Cement Hydration Processes to Undergraduate Students

Lisa E. Burris, Kenneth C. Hover, Anton K. Schindler, Aleksandra Radlińska

Synopsis: Concrete continues to be the most widely used material in the world, second only to water. Concrete is used in most civil infrastructure systems, but it often remains inadequately understood by the profession. For civil engineers to adapt to a world requiring ever-increasing efficiency, durability, and sustainability, and in which novel material formulations and products are introduced monthly, engineers must be able to make decisions as to the acceptability of these materials, and their effect on the performance of civil infrastructure. Essential to that ability is students' understanding of the basics of cement hydration and its relationship to property development in the fresh and hardened concrete state. Towards that goal, this paper presents the basics of cement hydration, resources for learning more about the subject, and approaches to transferring knowledge to undergraduate-level students, through both lecture- and lab-based activities. Topics addressed include prioritization of topics for undergraduate civil engineering students to learn with regards to cement hydration processes, approaches to effective teaching of these topics including active learning in the classroom and laboratory, as well as knowledge exchange strategies, assessment techniques, and lessons learned from past experiences teaching these topics.

Keywords: portland cement, hydration, maturity, microstructure, active learning, in-class demonstrations, concept mapping, inquiry-based learning, daily quiz

INTRODUCTION

It is essential that civil engineers understand the basics of the cement and concrete system to adapt in a world where new materials are introduced for use in civil engineering infrastructure on a regular basis. Furthermore, shortages in aggregates and supplementary cementitious materials (SCMs) like fly ash, as well as concerns over embodied carbon dioxide (CO₂) in construction materials, necessitate use of alternative materials. Thus, it is essential to understand the effects of system composition and environment on hydration kinetics, fresh state, and mechanical property development, including strength, stiffness, and durability. It is challenging to teach cement hydration to students with little concrete experience in an understandable and engaging way due to the complexity of the subject. This paper provides direction towards the most important topics associated with cement hydration and quality resources an instructor can use to increase their understanding of the subject. Furthermore, several in-class, experimental, and assessment approaches are presented to help undergraduate civil engineering students understand cement hydration. For each technique, suggestions are provided related to where it best fits within the course, required supplies, and potential pitfalls and obstacles encountered by the authors.

OVERVIEW OF CEMENT HYDRATION

Cement hydration is a complicated topic; many of the mechanisms and factors influencing its progression are still not fully understood. A thorough explanation of cement hydration can be provided within a graduate-level course on cements, but this is likely not appropriate for an undergraduate concrete materials course. However, it is important for undergraduate students to grasp the basics of hydration and its relationship to several significant factors, including:

- Phases present in typical portland cements (C₃S, C₂S, C₃A and C₄AF), their reaction rates, and their contribution to setting, strength, and durability.
- Stages of hydration (initial dissolution, induction, acceleration, deceleration, and steady state).
- Primary hydration products (C-S-H, CH, AFt, AFm), along with their impact on setting, strength, and durability.
- Major influences on hydration kinetics (particle size/fineness, water-to-cement ratio (w/c), temperature, chemical admixtures (particularly retarders and accelerators), and sulfate levels (particularly the extremes associated with flash or false setting behavior).
- Impact of time, moisture, and temperature on property development in the fresh and hardened concrete state.

Many textbooks are available for those wishing for a more thorough understanding of hydration. These include Mehta and Monteiro's *Concrete: Microstructure, Properties, and Materials* (2017), Mindess, Young, and Darwin's *Concrete* (2003), Taylor's *Cement Chemistry* (1997), Neville's *Properties of Concrete* (2011), and PCA's *Design and Control of Concrete Mixtures* (Wilson and Tennis 2021).

In courses with more time available to focus on additional topics, instructors should consider integrating these ideas into further discussion of concrete applications, such as through: integration with the teaching of concrete mixture proportioning basics (typically based on the ACI 211 2009 method); additional discussion of the effects of curing and environment on heat release and property development at both early and later ages paired with calculations of evaporation rates, shrinkage, and creep; deeper discussion of the role, reactions, and factors contributing to reactivity, of supplementary cementitious materials (SCMs) such as Class C and F fly ash, silica fume, slag cement, and finely ground limestone powder (not a pozzolan but an increasingly prevalent concrete additive); and coverage of the most common durability issues (corrosion/chloride diffusion, alkali silica reaction, deterioration due to freezing and thawing, and sulfate attack), approaches to their prevention and mitigation, and the role of cement hydration processes and materials selection on porosity/permeability and pH within the system.

Many students have had little previous exposure to concrete materials prior to their first civil materials course. They may have also forgotten many basic chemistry concepts, such as influence of temperature, pH, and ionic concentrations in solution on chemical reaction kinetics and precipitation of solid materials. Even if they do remember, most students have not had a chance to connect those basic principles with the 'real-life' effects of these principles on the hydration process that occurs in concretes. This paper presents several approaches for connecting the chemistry of cement hydration with real-life observations students can make about the system; extrapolation can be used to understand these systems at work at larger scales.

TEACHING METHODS

Much of the material discussed in an undergraduate course covering cement hydration topics will be based around chemical reactions, crystallography, and understanding forces affecting materials at the microstructural level. These topics are quite different from most other classes that civil engineering students typically take during undergraduate studies. Active learning methods enhance student learning, especially in courses with a significant proportion of qualitative material and lecture content. This paper presents multiple approaches for incorporating effective teaching techniques, including active learning, into a concrete materials course. Further descriptions and discussion of these learning approaches are provided in Swenty et al. (2023). Types of learning techniques recommended for use in teaching about cement hydration include the following.

Use of physical artifacts

Physical artifacts are physical models or examples used to build new knowledge of cement systems from existing student knowledge of somewhat analogous systems. In-class demonstrations, in conjunction with typical lecture material can aid in connecting these somewhat abstract ideas to real applications. In general, use of in-class demonstrations has been shown to increase overall learning gains considerably when compared to lecture-only presentation formats (Sokoloff and Thornton 1997, Sharma et al. 2010, Wojcik et al. 2012). When used effectively, in-class demonstrations using physical models can illustrate important aspects of a course in a practical and relevant way, make effective use of classroom time, lead to increased student involvement in class, and build rapport between the class and lecturer (Kresta 1998, Sokoloff and Thornton 1997, Sharma et al. 2010). Students also tend to remember content from visual demonstrations and experiments conducted during lecture better than concepts discussed only on slides or verbally (Kresta 1998).

Inquiry-based experiential learning

In an inquiry-based learning approach, students pose and then answer their own questions or problems. Inquiry and project-based learning in a concrete materials course extends learning through thoughtful engagement with small-scale cement systems and collection and analysis of data generated by those systems. In comparison to the traditional classroom setup, where an instructor lectures for most of the time and students must attempt to learn the topics presented, inquiry-based learning places the instructor in the role of *facilitating* knowledge acquisition, rather than as the sole provider, while students become actively involved in the discovery and creation of knowledge. Inquiry-based learning can be accomplished through experimental research-resembling activities and has been shown to lead to both deeper levels of learning and more satisfaction and feeling of accomplishment in students (Williams 2015, Jungmann 2019, Uziak et al. 2016).

Interactive assessment methods

Whereas traditional assessment methods typically aim only to assess the level at which students have understood and learned course material, more learning-centered assessment strategies can simultaneously accomplish multiple learning goals, helping students practice recalling course concepts and providing immediate feedback on the accuracy of their recall, creating opportunities to synthesize ideas to bring together multiple topics or apply learning to new situations, building in opportunities for collaboration with peers, as well as giving immediate instructor feedback on the success of student learning (Webber 2012). Learning-centered assessments can also be used to increase the frequency of student interaction with course material, which translates to greater long-term retention (Armour-Thomas and Gordon 2013). Learning-centered assessments recommended herein include use of “minute-paper” and “muddiest point” writing assignments, daily quiz homework, and quiz questions integrated within lectures.

Case-based learning integrated with real-world examples

Case-based learning uses historical or hypothetical situations to explore and/or validate topic theories and can be helpful in teaching material related to concrete materials and linking theoretical class ideas with their application in the field. Anecdotal stories and examples can be extended to include calculations of theoretical materials properties, compared with existing experimental data (from literature, or created by students), and employed to assess code requirements. Case-based learning examples that will be covered in this paper include the use of the maturity method and specification scavenger hunts.

TEACHING EXAMPLES

Details regarding several in-class demonstrations that the authors have found effective in teaching cement hydration concepts are covered in the following sections. To aid in implementation, the basics of the theory behind the demo, appropriate positioning of the demo within the course material, suggestions for where to obtain required materials, and suggestions for information and discussion topics for students following the demo are provided for each demonstration.

Physical artifacts

Hand-warming packets as examples of exothermic reactions such as the hydration of portland cement—Students sometimes assume that the chemical and physical behavior of portland cement is mysterious, rather than employing the same general principles of chemistry and physics that apply to all kinds of other systems. One simple and inexpensive way to demonstrate that the “heat of hydration” of portland cement produces similar heat release as other exothermic reactions is to have students experience the heat produced by small chemical hand-warmer packets, often available at checkout stands in many stores in colder months. The packets are activated by breaking open a separate container within the package, which mixes the ingredients and triggers an exothermic chemical reaction (often the rapid oxidation of iron particles in saltwater), producing sensible heat. This can be turned into a simple and quantitative experiment using a water-filled thermos bottle or other well-insulated container (serving as a low-cost semi-adiabatic calorimetry) by recording water temperature with a thermometer or thermocouple. The mass and initial temperature of the water is recorded, one or more hand-warmer packets are triggered and inserted into the water, and the lid is tightly closed. Data only need be recorded for a few hours to observe the maximum temperature rise of the water. One can then estimate the quantity of heat released by the hand-warmers over time. Heat released per kilogram of hand-warmer can be compared with the common range of values of heat of hydration per kilogram of cement. From this comparison, students can appreciate how much more heat is released by portland cement than by the hand warmer. Similar comparisons can be made with various combinations of cement and SCMs. Estimates of heat release from cementitious mixtures can be obtained from Mindess (2003) and Poole et al. (2010).

Two-dimensional models of the volumetric proportions of cement and water in pastes of varying w/c (prior to hydration)—This simple demonstration can be used at the beginning of any discussion about w/c. The primary objective is to demonstrate that w/c is not an academic abstraction but instead, when converted to a volumetric ratio, it is a powerful indicator of how far apart individual cement grains are from each other. These initial gaps between cement grains (admittedly variable) are the starting point for the subsequent setting and strength development as hydration products must cross these gaps. Subsequently, durability develops relative to the narrowing or blocking of gaps to reduce permeability and related transport properties.

In this demonstration, examples of which are shown in Figs. 1a and 1b, two-dimensional (2D) models are used to represent volumetric proportions of cement and water in pastes of varying w/c. All that is needed is a clearly defined, visible boundary representing the total volume of cement paste and contrasting objects used to represent cement particles. The ratio of the cumulative *areas* representing solid particles (spherical balls in Fig. 1a) to the total *area* of the box is taken as the ratio of the *volume* of solid particles to the *volume* of the total cement paste. By varying the size and number of the randomly placed particles, the volume proportions of pastes could be modeled for any desired value of w/c ratio. Volume proportions are calculated by conversion from w/c ratio weight proportions. For teaching purposes, a shallow plastic or cardboard box was used to represent the boundaries of a 2D slice of cement paste, and objects of contrasting color (or transparency) are sequentially placed in the box to represent the increasing volume-fraction of cement and the decreasing average spacing between cement particles associated with various w/c ratios. This approach has been successfully used with ping-pong balls, poker chips, and coins to represent solid particles (Fig 1b); a US dollar bill with US penny “cement particles” has even been employed. Nine pennies on a dollar bill represents a scale model of a cement paste with a w/c = 1.0. Eighteen pennies on a dollar bill represents a w/c = of 0.33. Taking this approach a bit further, homework problems may also be assigned to US students using a more stereo-logically accurate blend of dimes, pennies, nickels, and quarters to represent the variation in typical cement particle size distribution; analogous homework problems have been assigned to international students, where they are tasked to come up with similar demonstrations using their own coinage and paper money.

To use this demonstration in class, the instructor may begin by showing the boundary enclosing the total simulated volume of cement paste with no particles present, showing a cement paste that is 100% water and 0% cement, with a

w/c of infinity. As the particles are added one-by-one, the instructor announces the mass ratio w/c represented by the model, eventually getting into practical ranges for residential, then commercial structural grade, then ultimately high-performance concrete. This is also a good opportunity to show the w/c thresholds of 0.55, 0.50, 0.45, and 0.40 as required by Chapter 19 of the ACI 318 (2019) building code for durability in response to various exposure conditions. Both strength and durability implications of w/c are made clear via this simple demonstration as the gaps between particles get smaller and smaller with decreasing w/c, making it easier for particle-to-particle connections essential to developing strength and reducing transport (through reduced permeability) to occur. It is also important to point out that, with this model, the total paste volume is being held constant, such that any increase in volume of solid particles must be matched by an identical decrease in the volume of water. Under these circumstances, it is likely that there will be less workability associated with the decreasing w/c, requiring compensation via other adjustments to the mixture, such as the use of chemical admixtures.

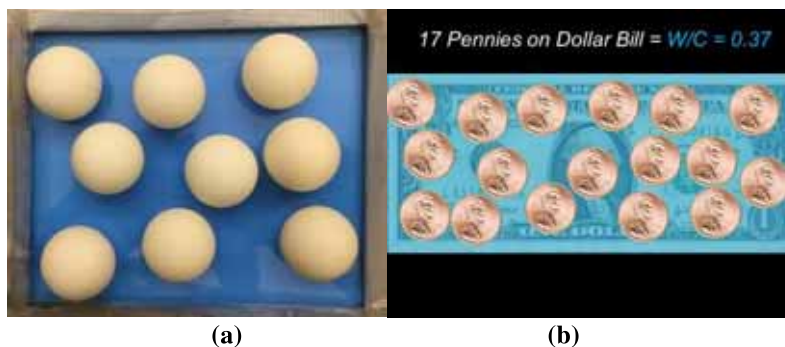


Fig. 1—(a) Ping-pong balls represent cement grains in a box that represents the volume of the cement + water paste (blue background represents water). The cumulative projected area of the 9 balls = 17.4 in². Total area of box = 46.3 in², for a cement area ratio = 38%, equivalent to the cement volume fraction in a paste with w/c = 0.53. (b) The same concept can be applied to readily available standard sizes and shapes such as a dollar bill and pennies.

Simple physical models of hydrated (or partially-hydrated) portland cement—Understanding the microstructure of hydrated cement is essential for understanding its performance. The simple models shown in Figs. 2, 3, and 4, in combination with the scanning electron microscopy photograph (Fig. 2a), can be used to convey understanding of C-S-H microstructure, knowledge of which is essential to understanding the behavior of concrete. To further embed this lesson, at the presentation of these models handfuls of the small plastic spike balls shown in Figs. 2 through 4 may be thrown out to audiences. Students never seem to forget this, well after graduation.

Fig. 2a shows hydrated portland cement with a characteristic development of hydration products “growing” from the increasingly occluded surface of the cement particles. Developing inter-particle connections that give rise to strength and other mechanical properties are visible, as are the inter-particle void spaces that give rise to transport properties and most of concrete’s durability challenges. Given the need to explain this characteristic microstructure as a key to the fundamental behavior of portland cement concrete, three-dimensional (3D) hand-held models, such as are shown in Fig. 2b may be used. At an ACBM conference in 1993, Professor Francis Young at the University of Illinois suggested that the models could be made more accurate by reducing the length of the hydration products (toothpicks) relative to the diameter of the cement grains. This extraordinarily useful suggestion from one of the giants in the field led to adoption of the plastic models shown in Figs. 2b - 2d, Figs. 3a and 3b, and Figs. 4a and 4b. The reader is invited to compare the microstructure in Fig. 2a with each of the other simplified teaching models.

In addition to general demonstration of C-S-H microstructure, use of multicolor “Spike Balls” (Figs. 3a and b) can help to reinforce the notion that portland cement is a heterogeneous blend of at least four distinct minerals. Further, naturally occurring burrs (Fig. 3c) that connect to each other (and everything else they touch) suggest that bonds develop between adjacent grains of portland cement as result of the growth of hydration products. Such natural connections were the inspiration for the development of the indispensable modern material known as Velcro, shown in Fig. 3d. Strips of Velcro used in-class demonstrations show that the strength of the Velcro bond depends on the proximity of the two strips similar to lower w/c portland cement paste mixtures, which result in reduced distance between cement particles and thus higher strength. Further, the strength of the Velcro bond increases with the degree to which the opposing faces have been compressed, which is analogous to the benefit of consolidating concrete.

Other Velcro-based analogies such as the use of “Bunchems,” (Figs. 4a and b), or ping-pong balls and stick-on Velcro tabs (Fig. 4c) can be used to demonstrate bonding of adjacent particles by hydration products. Similarly, paste-behavior can be simulated using playing cards to represent C-S-H “sheets” bound by Velcro tabs representing the interlayer or zeolitic water (Fig. 4d).

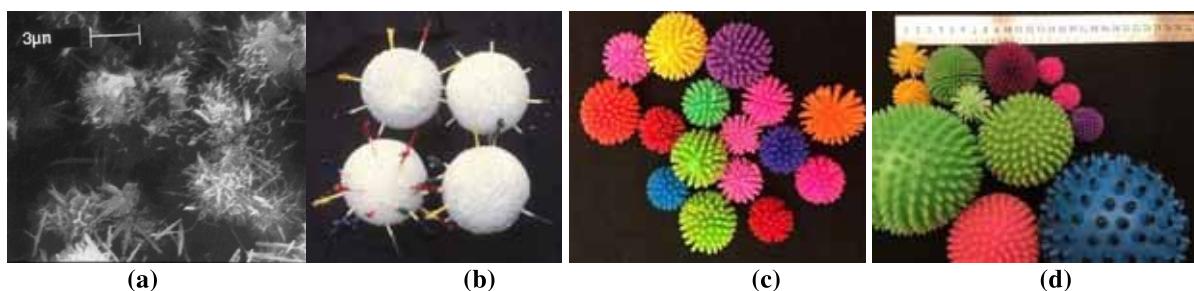


Fig. 2—(a) Scanning electron microscope image of partially-hydrated portland cement. (Eric Soroos, Cornell University) **(b)** 2.75 mm diameter Styrofoam balls (available in fabric and craft shops) into which cocktail toothpicks have been inserted to represent products of hydration. **(c)** Plastic “Hedge Balls,” “Porcupine Balls,” or “Spike Balls,” typically available online in either 25 or 32 mm diameter and up to 144 per bag. **(d)** Much larger versions up to 3 to 6 in. in diameter are available in toy stores or pet stores.

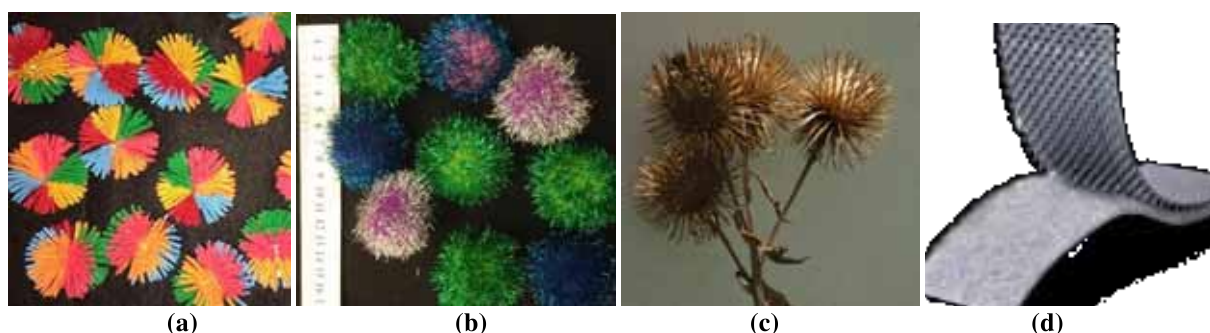


Fig. 3—(a) Multicolor “Spike Balls” help to reinforce the notion that portland cement is a heterogeneous blend of at least four distinct minerals. **(b)** Originally intended as cat toys and available in pet stores, these models bear and uncanny resemblance to the SEM image of Fig. 2(a). **(c)** Naturally occurring burrs. **(d)** Strips of Velcro.

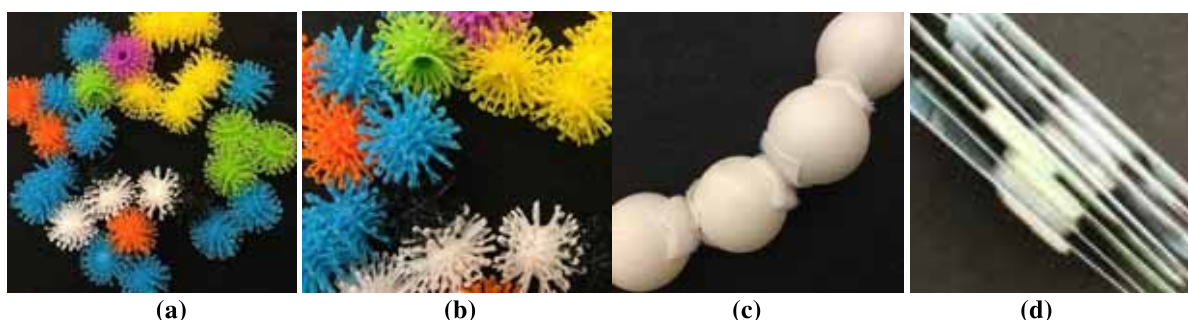


Fig. 4—(a) and (b) The ultimate, handy model of hydrated grains of portland cement is the commercially available children’s toy known as “Bunchems,” which are manufactured reproductions of the natural burrs, giving them the advantage of actually sticking together. **(c)** Functional model of cement grain bonding. **(d)** Playing cards and Velcro used to simulate C-S-H sheets bound by zeolitic water.

Portland cement fineness—The relationships between particle size and surface area are essential to understanding the impact of particle size on cement hydration, in addition to aggregate proportioning, mixture proportioning, cement and SCM relationships (including filler effect) and rebar-to-concrete bond strength. A useful exercise is to calculate the total surface area of any cumulative mass of spherical particles as a function of total mass, density, and average particle diameter. The principle that cumulative surface area increases rapidly with a

decrease in average particle size is critical in concrete technology at scales varying from coarse, intermediate, and fine aggregates, all the way to air bubbles, cement particles, and SCMs. This principle explains the mechanism behind why fine grinding of cement (such as with Type III cements) leads to higher water-demand and chemical admixture dosages, increased gypsum needs, faster setting, and high early-age strength gain. All these effects are explained by the increased surface area of the finer cement, allowing increased contact between cement and water, i.e., increased area of reaction per unit mass.

For the 95% of the students in the class who truly enjoy (and thrive on) coffee, many of whom consider themselves to be quite the coffee-connoisseurs (and may even be working as baristas), it can be effective (and fun) to compare the influence of cement fineness with the fineness of coffee grinds and its effect on the produced coffee beverage. The primary reason for grinding coffee finer is to increase the surface area and thus increase contact between the ground coffee and the hot water. The finer the grind of the coffee, the more rapidly the hot water can extract flavor. The short contact-time when making espresso requires a finer-grind, which also permits more thorough extraction of flavor. This is the reason that a finer grained powder also leads to a stronger (and sometimes bitter) coffee. In cement production, the grind fineness varies with cement type (specifically between Types I and III). In addition, portland cement fineness is typically reported in terms of Blaine Fineness, which relies on the principle that in a packed-bed of cement particles, the finer the particles the more difficult it is to pull air through the bed (under a low-pressure difference). The longer it takes air to pass through the bed, the smaller the particles, and therefore the higher the fineness. The same principle applies to coffee, because over-grinding the coffee slows the hot water penetration rate and finely packed espresso requires a high-pressure machine to force the water through.

Influence of temperature on the rate of hydration—The following introductory discussion is used very early in the concrete materials course to illustrate the exponential influence of temperature on the rate of hydration of portland cement. At the same time, it is also used to reinforce the notion that cement hydration is a “growth process.” This discussion must immediately be followed, however, by an explanation of the more complicated influence of temperature on rate of strength-gain, which has a role both in the lab and in-place concrete construction.

As with most chemical and biochemical reactions, increasing the temperature of a concrete sample will increase the rate of that reaction. An increase of cement-paste temperature by $\sim 10^{\circ}\text{C}$ approximately doubles the reaction rate. Decreasing paste temperature by $\sim 10^{\circ}\text{C}$ approximately halves the reaction rate. In both cases, the “rate” pertains to the formation of hydration products (not necessarily development of strength or other mechanical properties). This exponential relationship is shown in Figs. 5a and b. To help students understand that this temperature-sensitivity is common to many other reactions and processes, Fig. 6a includes similarly normalized growth rates for both turfgrass and corn. Observe that in the temperature range from about 20 to 25°C (68 to 75°F) the influence of temperature on growth is nearly identical for cement, grass, and corn. These observations invite discussion about how typical changes in jobsite temperature can significantly impact rates of cement hydration.

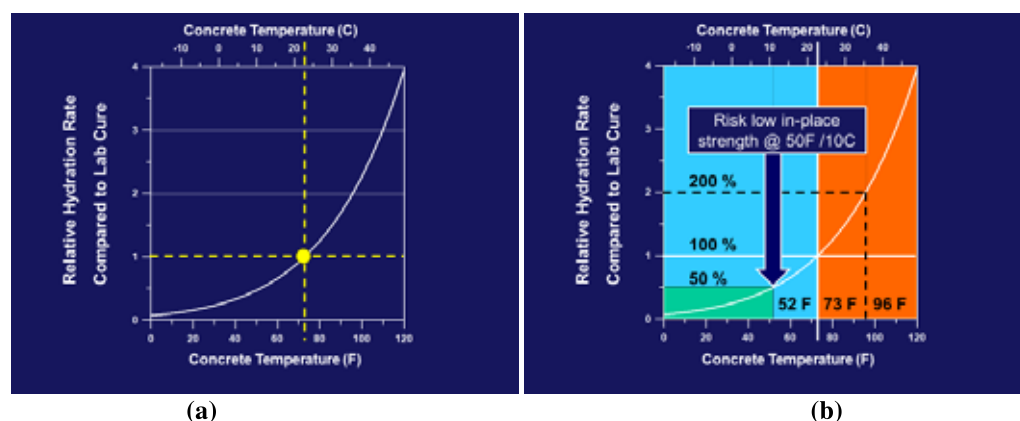


Fig. 5— (a) Rate of hydration for an ordinary Type I portland cement relative to the rate observed at standard laboratory temperature of 23°C or 73°F . (b) The influence of temperature is further emphasized by the fact that relative to standard laboratory temperature, the rate of hydration will double at about 36°C (96°F) and will be cut in half at a seemingly moderate temperature close to 10°C (50°F).

The curve in Fig. 6b shows that concrete strength at an age of one-day reflects the thermal-sensitivity of rate of hydration just described. However, the relationship is literally turned upside down at later ages in which higher concrete temperature over the full curing period leads to a decrease in concrete strength. This decrease in later-age strength as a consequence of higher concrete temperature is the result of reduction in the quality of the Velcro-like bonds (such as are modeled in Figs. 4c and 4d) that develop between and among the grains of portland cement when those bonds are forced to develop at a faster rate, thus leading to reduced long-term strengths (Klieger 1958; Verbeck & Helmuth 1968; Neville 1981; Wilson and Tennis 2021).

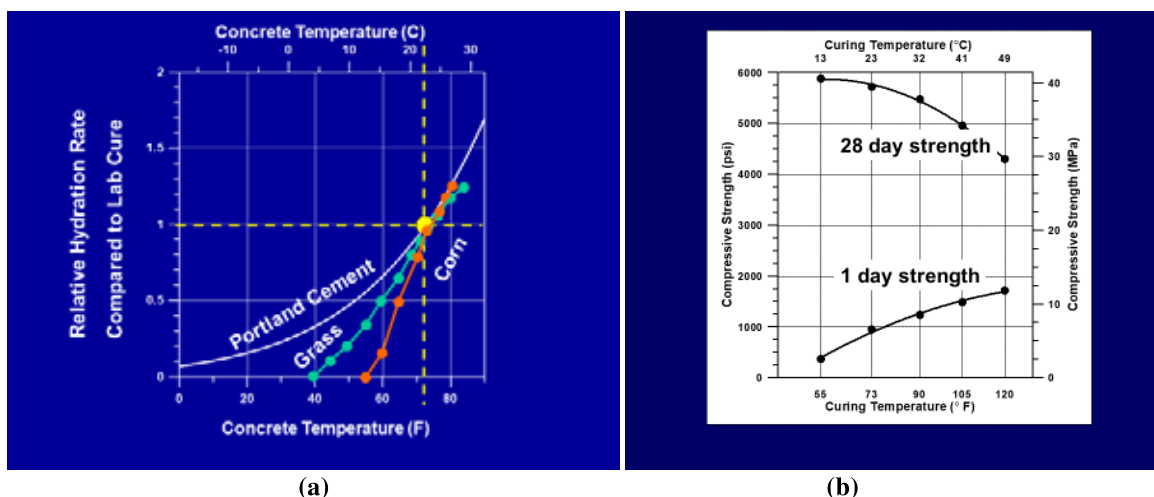


Fig. 6— (a) Augmenting the curve for the influence of temperature on cement hydration with two common biochemical reactions. Just as each corn hybrid will have a uniquely different sensitivity to temperature, each concrete mixture will have a similarly unique thermal-sensitivity. (b) Comparison of the effects of temperature on concrete compression strength at early- versus later-age. [Courtesy PCA]

Inquiry-based experiential learning

Low-tech calorimetry—Calorimetry is perhaps one of the best ways to help students understand the hydration of cementitious systems. A calorimeter works by tracking heat release of a system of paste, mortar, or concrete over time. Heat release can be used to determine relative effects of various cementitious materials and admixtures on setting, differentiate between the different stages of hydration, and can give indications of effects of the reactivity of various materials on the overall hydration of cementitious system. Research-grade calorimeters can be great tools students can use within a course on cement hydration to develop and answer their own research questions. However, for classroom learning, a research-grade piece of equipment is not generally necessary, and a low-tech, low-cost calorimeter can be created using lidded tin cans filled with spray foam insulation (Fig. 7), thermocouple wire and a data acquisition system capable of tracking voltage or an iButton. This system is also transportable, allowing the setup to be brought directly into the classroom.



Fig. 7—Paint cans used for low-tech calorimetry experiments. Paint cans are filled with expandable foam to insulate it from exterior temperature. Mixed paste samples are placed in removable Styrofoam cups to facilitate easy sample preparation and cleanup following the experiment.

In this experiment, students can be asked to create a question or hypothesis and determine how to test their hypothesis based on heat release. They can also, more simply, be asked to design mixtures to determine the influence of w/c, chemical admixtures, or SCMs. Students could also be allowed to be creative about what materials are included to substitute for either the cement or liquid portion of the mixture and challenged to determine why that material alters the system's kinetics. Some examples could include food or drinks, or materials such as wood shavings, ground plastic, cardboard, or glass. Typically, the goals of these experiments are to:

- 1) Promote students' curiosity with regards to cement hydration and the effects of ingredients and mixture proportions and allow them to ask and answer some of their own questions.
- 2) Allow students to test the effects of several substances on hydration, analyze the data, and understand the results.
- 3) Gain hands-on experience developing and conducting experimental investigations.

Low-tech Calorimetry Example Problem Definition:

Cement hydration reactions are exothermic. In a large concrete structure, such as a dam, the concrete temperature can rise considerably, for several reasons. First, the more cement present in a concrete element, the more heat is produced. Second, the concrete in the interior of a massive element is insulated by the exterior concrete, preventing the heat from dissipating, and increasing the temperature. Third, higher temperatures increase the rate of the hydration reactions, quickly creating even more heat.

Excessive heat in a concrete element can result in extensive damage. If the interior of a concrete element is hot and the exterior is cool, then the differences in thermal expansion in these regions can result in strains that exceed the tensile strain capacity of the concrete and cause "thermal cracking." This is in addition to strength reduction due to high early temperature mentioned previously. Another potential problem is called Delayed-Ettringite Formation (DEF). DEF is a potential long-term concrete durability problem when early-age concrete temperatures exceed 70°C in moist, plain portland cement concrete structures (Taylor et al. 2001). A detailed discussion of the DEF mechanism is provided in ACI 202.2R-16, Section 6.2.2.2.

Example Experiment Instructions:

Materials

Each group of students will mix and test one cementitious paste. Data from all groups will be distributed for analysis by everyone. Variables to be tested include w/c, admixtures, Class C fly ash, Class F fly ash, and silica fume.

Equipment

Latex gloves, plastic cup for mixing, popsicle stick or spoon for mixing, syringe, to measure out mixture water, Styrofoam cup and insulated can for temperature measurements, temperature monitoring device (typically Type K thermocouple or i-Buttons)

Mixing

1. Dump a baggie of cement/SCM material into plastic cup.
2. Measure the necessary amount of water (and admixture if relevant) using the syringe and place it in the plastic cup with the cement/SCM. Note the time of contact between cement and water.
3. Stir mixtures with sticks or spoons until the cement paste is uniform (1 minute).
4. Make notes on the consistency and fresh temperature of the paste.

Testing

1. Weigh the empty Styrofoam cup.
2. Place all the cement paste inside the Styrofoam cup and weigh the full Styrofoam cup.
3. Insert the temperature sensor into the center of the paste. Note the time of insertion.
4. Place the Styrofoam cup inside the insulated can and close the lid.
5. Allow sensor to record temperature data for at least 3 days.

Reporting Results

1. Prepare a table with information about all of tests performed. Include the materials used and proportions, sample weights, and fresh temperatures.
2. Prepare the following plots. Be sure to label each mixture with the appropriate composition.
 - a. Temperature (°C) versus time (hr) for all the mixtures (in one plot).
 - b. Temperature (°C) normalized by sample weight (g) vs. time for all the mixtures (in one plot).
 - c. Temperature (°C) normalized by the cement weight (g) (i.e., correct for w/cm and SCM) versus time for all of the mixtures tested (in one plot).

- d. Cumulative heat (i.e., area under curve) versus time including all the mixtures tested. Subtract room temperature from the measured temperature and normalize by cement weight.
3. Explain any observed differences between plots 2a-2c. In other words, does normalization remove any of the differences between samples or does it make any more apparent, and why?
4. Which mixture did you expect would release the most heat? Why? Did the results match your expectations? Explain. (When discussing expected results, you must reference the source of the information that led to your expectations, such as class notes, textbook, or other creditable source.)
5. Which mixture did you expect would release the least heat? Why? Did the results match your expectations?
6. Using the cumulative heat evolved curve, determine an approximate ranking of 24-hour, and the 3-day strengths for the mixtures. Does this meet your expectations for which mixture should develop the highest strength?

Understanding and Explaining the Results

Calorimetry data are readily interpretable for evaluating the effects of various mixture parameters on hydration timing and extent. Several parameters can be investigated using isothermal calorimetry, including the questions posed previously, as well as: a) the time required for the mixture's major reactions to begin and for the material to enter the acceleration stage; b) the time required for the mixture to reach its peak rate of heat release; c) the magnitude of the rate of heat evolution at the peak; and d) the cumulative heat released over a particular amount of time (typically 24 and/or 72 hours).

Data from this experiment (Fig. 8) clearly show changes in peak heat release and timing of primary hydration reactions based on materials and their proportions. One typically expects to see decreases in total heat due to dilution of the total amount of heat-releasing phases when incorporating materials other than portland cement and slag cement, which both react with water. Materials such as Class F fly ash and limestone serve primarily to dilute the heat of hydration contribution of the overall mixture at very early ages (thus the reason they are often used to reduce early-age heat of hydration in mass concrete mixtures). High dosages of some water-reducing admixtures (in the case of Fig. 8, "WRA") may cause shifts in the hydration peak to later times, as will retarding admixtures. Accelerating admixtures will have the opposite effect, shifting the heat release peak earlier.

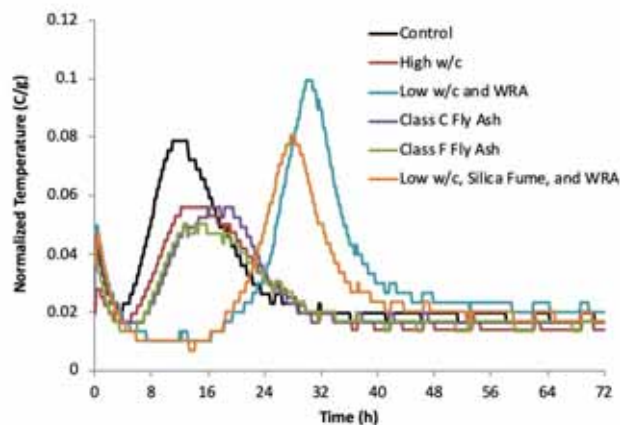


Fig. 8—Low-tech calorimeter data from a concrete materials course module on cement hydration.

In-class exploration of cement paste properties: w/c, workability, high-range water-reducing admixtures, and heat of hydration—A similar, but slightly simpler and cleaner version of this experiment can be used to demonstrate both effects of mixture proportions on workability, as well as understanding heat of hydration using mixtures mixed in Ziploc bags. This experiment can be used in the first or second lecture of the course, or the first or second lecture in the concrete section of a broader civil materials course, to help give the students a literal “feel” for the material to be studied. This type of hand-eye-brain connection helps students distinguish among cement, paste, aggregate, mortar, and concrete, in addition to addressing the materials’ heat generation, all without having to go to the laboratory and without risking a classroom mess. The transition from fluid to solid is demonstrated by bringing the bags of hardened paste, mortar, or concrete into the next lecture. To help students unforgettably understand the differences among material types, the demonstration can be modified to include aggregates or fibers, or excluding portland cement to conduct the experiment with slag cement or fly ash only, for example.

To use this technique, the instructor prepares several transparent Ziploc bags with premeasured masses of portland cement (with or without SCMs, fibers, or chemical admixtures), to which water is added to achieve the target w/c. For a simple version of this demonstration, use equal volume paste samples (Table 1). After removing most of the air, each bag is sealed and temporarily put inside a second transparent Ziploc bag. The second bag is used as backup in case the first develops a leak. At this point, the bags are passed around the room so that the students can mix the paste by thoroughly kneading the contents. As the bags are passed, students get an immediate tactile sense for the fluidity or workability of pastes at various w/c values. Shortly after mixing, students can begin to sense an increase in the paste temperature, which can be measured and graphed as described previously, through use of thermocouples or iButtons. By the following lecture, the same bags can be passed around for the students to feel the hardened paste. This demo can be completed in about 15 minutes of class time. In addition to the passed samples, the instructor can also make a set of companion samples for measuring heat, similar to the low-tech calorimetry experiment described previously.

Table 1—In-class workability and calorimetry demo material proportions

Item	Paste Sample A – low w/c	Paste Sample B – high(er) w/c	Paste sample C – 50% fly ash	Paste Sample D – 10% silica fume
w/c	0.30	0.42	0.42	0.42
Portland cement (g)	500	420	200	373
SCM (g)	0	0	200	41.4
Water (g)	150	176	168	174
Volume (mL)	310	310	310	310

Follow-up discussion with students

- **Workability:** Compare the workability of the low and higher w/c pastes. The low w/c sample requires much more energy and time to mix thoroughly. Ask students to visualize how difficult working this sample would be if another 1000 g of sand was added! Emphasize that to use a paste with a w/c of 0.30 in concrete chemical admixtures will be required to produce sufficient workability for conventional placement techniques.
- **Hydration:** Compare the temperature histories of the two paste samples. Discuss the effect of using these two w/c on hydration. Compare parameters such as the peak temperature and when the temperature initially rapidly starts to increase. Emphasize that cement hydration is an exothermic reaction. It should be clear that the paste sample with the lowest w/c (and highest cement content) reaches the highest temperature.

In-class demonstration of workability – another example—If possibility of spills and potential cleanup are not a major issue, the experiment on workability can be shared with the students using disposable cups and by pouring the fluid paste from one cup to another in front of the audience to allow students to visually assess differences in flowability of various mixtures.

Students are handed a laboratory sheet, where the date, time, and room temperature are to be recorded. Subsequently, groups of 3-4 students are handed clean cups – 8 oz capacity, a stirring rod made of plastic or other suitable material, 1 syringe or eye dropper, 1 measuring container – 50-100 g capacity, 2.0 mL of high-range water-reducing (HRWR) admixture, 300 g Type I cement, marker, and a container filled up with water. Students are asked to mark the cups as #1, #2, and #3, and fill each cup with 100 g of cement. Cup #1 is a control mixture, and students are asked to add 30 g of water and mix the paste thoroughly, noting their observations on paper (very low workability and hard to mix thoroughly). They are also asked to determine w/c for this paste. Next, they mix 40 g of water into a second cup, noting the changes in workability and w/c. Finally, they are asked to use the same ingredients as in cup #1, but this time HRWR admixture is added into the mixing water – this will become the most workable and flowable mixture of all. In large classes, a couple of groups can be formed to conduct the demo in front of the class and pour each mixture out of the mixing cup into a tray or large container. Students are often surprised to see effectiveness of HRWR admixture and as such, the lesson and concepts taught become memorable.

Interactive assessment techniques:

Use of learning-centered assessment techniques are another active learning technique that can increase student engagement with, and overall learning of course material. With learning-centered assessments, instructors can assist students in organizing course material and synthesizing learning, promote staggered learning and link the less

obvious applications of chemistry-based concepts associated with cement hydration back to its impact on real-world concrete performance. Several learning-centered assessment activities that can be used when teaching about cement hydration include use of concept maps, reflective writing (“one minute”, or “muddiest point” papers), and frequent quizzes, which promote more regular and consistent engagement with course material.

Concept Mapping—Concept maps have been shown to be an effective tool for linking difficult and complicated topics (Valdes-Vasquez et al. 2010, Barrella and Watson 2016, Turns et al. 2000). When teaching concepts related to cement hydration, it can be difficult for students to understand the context of each of the smaller topics warranting discussion, including: hydration stages, the influence of each of the unhydrated cement phases on hydration, effects of curing, chemical admixtures, and SCMs on properties of the hardened binder, etc., and how these concepts relate back to the overall big picture with regards to cement hydration and hardened properties development. Concept mapping can be one approach to summarizing the connections between concepts and properties.

The general approach to using a concept map is to start out simply, with only one branch, or with only the central topics, and build in complexity. Revealing the entire chart at once can be overwhelming and should be avoided. For instance, in the example in Fig. 9, building of the map starts with the “cement hydration” concept, after which the typical hydration curve and five stages (initial dissolution, induction, acceleration, etc. (in white)) are introduced. After that, the map builds out to each of the unhydrated cement phases (shown in pink) “cement hydration is affected by ‘phase content’” and the overall effect of each phase on hydration rate and strength and/or microstructural development, which can be further related back to the stage in which most of their reaction occurs (should the instructor wish to take the map this far). The concept map is further built out in later lecture stages with the discussion of each of the other factors affecting cement hydration: sulfate content, SCMs, w/c, admixtures, mixing energy, temperature, and curing.

One difficulty in implementing concept maps in the classroom is the question of ‘how.’ Several methods include: (1) stopping periodically during lectures to add to the map; (2) creating the map as a summary activity at the end of a unit; (3) providing students a list of topics and have them create the maps and discuss connections between each of the topics with each other; (4) providing maps with blanks for students to fill in. Approaches (3) and (4) are undeniably the preferred approaches, turning the concept map into an active learning activity. However, it may be difficult for students who are already struggling to learn and understand the material to simultaneously must figure out how to create a map (perhaps for the first time) and also determine how concepts are related. When choosing to utilize concept maps in a course it is recommended that instructors allow students multiple opportunities to practice creating and using the maps prior to using them for course grades.

Targeted lecture material quizzes and the one-minute quiz—A typical course in concrete or construction materials is very likely to make liberal use of slides, images, short videos, and perhaps even field trips. Instructors can make the mistake of assuming that students truly understand what they are seeing just because an image has been shown on the screen in the classroom (with salient details highlighted by the instructor) or a scene that has been pointed-out in the field. This is particularly true with photographs of raw materials extraction, cement manufacturing, concrete production, or concrete construction, where each image may be worth a thousand words but only 100 of those words were the intended focus of the instructor. Quizzes are a useful tool to highlight intended foci from class, with the instructor formulating questions based on the same images shown in-class along with a series of questions about the image. One format is to ask questions that require only a brief answer but to leave the image on the screen for perhaps only one minute before moving onto the next.

The ‘One-minute quiz’ is another commonly employed technique that can help with material recall or highlight to students, areas in which they should spend additional study time. One-minute quizzes have been shown to increase student engagement in lectures, give opportunities for students to synergize and practice recalling learned information, and provide regular feedback on their learning progress (or confusion), both to students and the instructor (Chizmar and Ostrosky 1998, Bartlett and Morrow 2001). Typical questions for the one-minute quiz are “What is the most important thing you learned today?” which can help determine if students are focused on the correct topics or “What is the muddiest points still remaining at the conclusion of today’s class” which discerns student confusion. Use of a “Think-Pair-Share” model, in which students answer the question, then discuss or explain their answer with a partner before the instructor brings the discussion back to the full class, has also been shown to extend student’s conceptual understanding even further (Kothiyal et al. 2014). When answers are to be

collected and evaluated by the instructor, internet-based applications such as TopHat, Poll Everywhere, and Kahoot can help decrease time associated with distribution and collection of paper quizzes, time for students to write down the problem on their paper, and can also aid in grading, especially when multiple-choice questions formats are used (fill in the blank type questions can be counted wrong by software from simple spelling mistakes or nomenclature differences between the instructor's input answer).

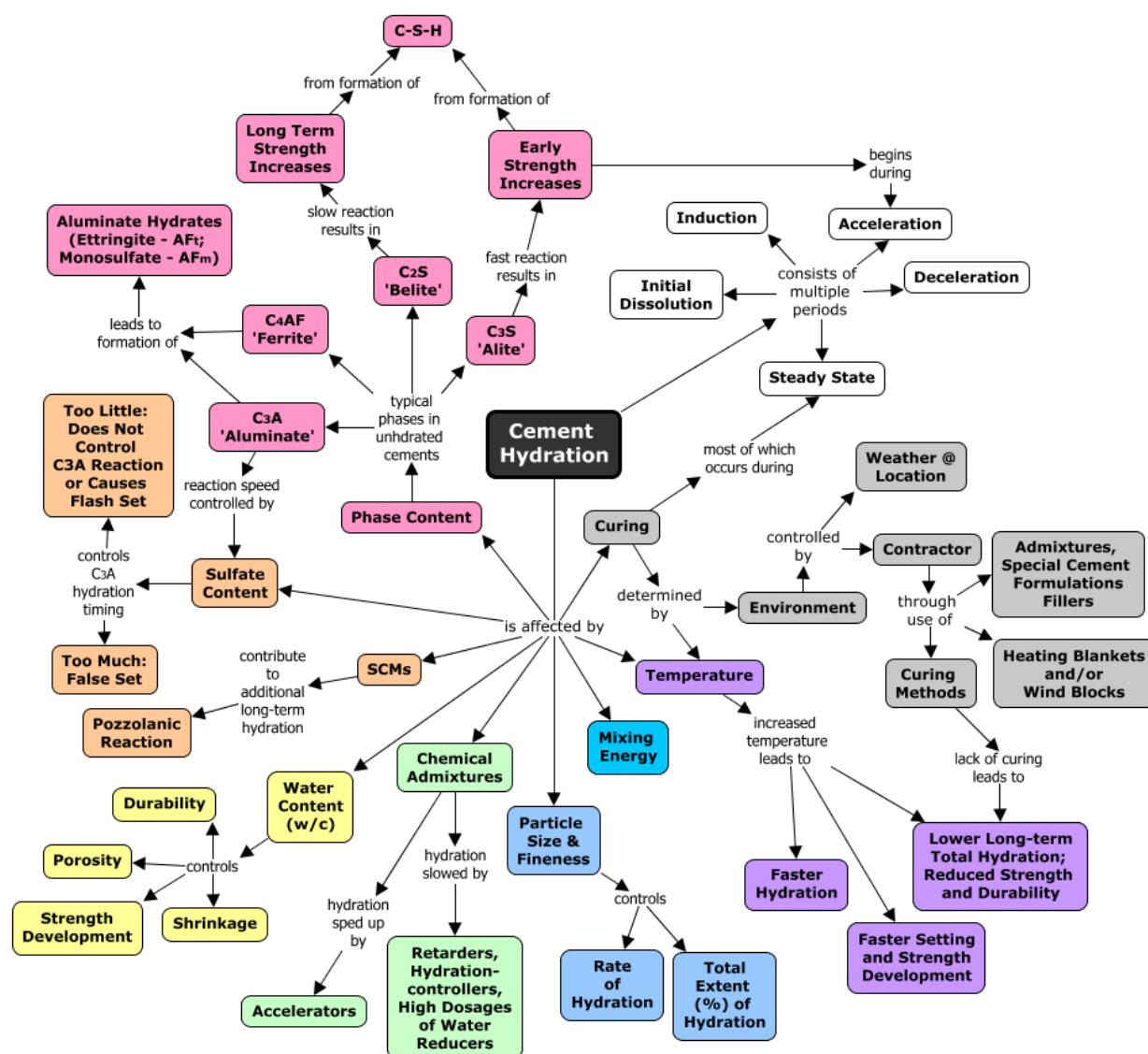


Fig. 9—Example cement hydration concept map, where each color corresponds to a different factor controlling the cement hydration process, including: phase content (pink), other phases, SCMs and sulfate (orange), water content (yellow), chemical admixtures (green), particle size and mixing force (blues), temperature (purple), curing (gray), hydration stages (white).

Daily quizzes—Civil engineering materials classes are somewhat unlike other civil engineering courses, with a much greater proportion of time spent on qualitative learning as opposed to the calculation-heavy models of other courses such as reinforced-concrete design or strength/mechanics of materials. Due to this variation from typical engineering course norms, it can be a challenge in and of itself for students to learn how to study for and learn not only the immense amount of technical terminology and jargon associated with the field, but also the deeper theoretical reasoning necessary to understand and apply concrete materials learning to real world situations. Not having much experience with this type of course material format, students often do a poor job of reviewing between

classes and remembering ideas discussed in previous lectures. This leads to an inability to think through and discuss new information presented without having a solid understanding of past material. In addition, most students delay preparation until only a few days prior to each exam and are then overwhelmed by the quantity of material to both memorize and understand. Further, traditional homework assignment lengths can be arduous (and boring) to review in class, requiring all feedback to be given individually to students, or not at all. Perhaps this is feasible for a small course, but in courses with 50 or more students, this represents a significant time commitment by the instructor and precludes the help of graders.

To change this pattern of procrastination, traditional homework formats can be shifted into ‘daily quiz’ assignments. Following each lecture, approximately five questions are disseminated to the students through the course website. Questions should reinforce topics covered in lectures and provide additional practice and exposure to difficult and key concepts. However, daily quiz questions also sometimes ask students to investigate new material that time did not allow coverage of in lecture further. This extension of lecture material prompts students to think more deeply about a topic or can serve as a mechanism for instigating students to apply learning to analyze a more complicated situation. Questions can also serve as introductions to future topics for which students may benefit from previewing before they are broached in lecture. However, ‘extension of knowledge’ questions should be assigned along with direction to where students can find the knowledge. Expecting students to search on their own often leads to student frustration or nonengagement with the question. Questions can be assigned slightly differently each semester based on course pace and in-class discussions, but most questions can be reused each semester, minimizing instructor work after initial question development.

For the daily quiz question sets, students are asked to answer each question and are then quizzed over one of the five questions at the beginning of the following lecture. Quizzes are open notes and open book, lessening the stress of the activity – if students have taken the time to answer the questions prior to class, they will be able to correctly and quickly solve the quiz and obtain the points. Quizzes are graded using a pass/fail format, to minimize grading time. Online polling systems can further accelerate grading using the grading options of the software, or in a spreadsheet using the “Find” function, or conditional formatting to locate keywords within answers. Daily quizzes are weighted quite highly as a portion of the total grade to inspire students to take them seriously and complete the activity each day; 20% of the total grade seems to make it ‘worth it’ for students to keep up with quiz questions and attend class to answer. As a final portion of this activity, answers for all the questions are reviewed each day following quiz collection to give immediate feedback and allow students to ask questions and/or discuss the answers. Daily quizzes are timed and short, typically 5 minutes or less depending on question complexity.

Other approaches can include varying the format to include teams of two to three students. One sign that the team-quiz is working is when there is a great deal of chatter as team members express their opinions as to how to solve the problem (one can readily observe the process of students teaching each other). When there is no chatter, it is obvious that the students are primarily working on their own, but collaboration is encouraged by requiring that only one quiz be submitted per team and that all team members will receive the same score. Another methodology is to distribute the quiz with the instructions that it is an individual quiz. Partway through the exercise, inform the students that they are to team-up, collaborate, and submit what they believe to be the best answer. This is generally successful as indicated by a much louder “buzz” in each team as the students work together. This has the advantage of forcing each student to come to grips with the problem individually and start thinking seriously about its solution prior to collaborating. When they get together, each of them has a good start on the problem and has an idea about how to reach a solution, like the “think-pair-share” teaching approach. This strategy cannot be used with every quiz, however, or the less motivated students could do nothing and might let other members of their team do the work.

Problem- and Case-based learning:

Maturity method—Maturity method is a technique used to account for the combined effect of temperature and time on the development of concrete hydration and mechanical properties (ASTM C1074 2019). After measuring the curing temperature and strength of cylinders at various ages (e.g., 1, 2, 3, 7, 14, and 28 days) the strength-maturity relationship can be established for a mixture. Next, the in-place concrete temperatures are measured and then the maturity method can be used to estimate the in-place concrete strength. This knowledge of the in-place strength development can be used to determine when to remove formwork, when to apply post-tensioning, open a bridge to traffic, etc. The popularity of the maturity method has increased and is frequently used in industry. Maturity roots the concepts of heat of hydration and strength gain to industry applications; it can both allow students to see the importance of understanding cement hydration and the effect of temperature on hydration,

as well as give them a real-life application for which to apply their learning. The following exercise can be used as either an in-class example of the application of the maturity method, a homework reinforcing the application of this concept, in conjunction with laboratory concrete mixtures, testing of strength development, or combinations of these approaches.

Maturity Method Example Problem Definition:

Develop a strength-maturity relationship by using the equivalent-age maturity method to determine the age at which a bridge can be opened to traffic. Assume the following conditions:

- Concrete property: Activation Energy = 45,000 J/mol
- Laboratory conditions used to test cylinders: Average curing temperature = 74°F
- Field conditions:
 - January placement: Average curing temperature = 50°F
 - March placement: Average curing temperature = 60°F
 - May placement: Average curing temperature = 85°F
 - August placement: Average curing temperature = 95°F
 - October placement: Average curing temperature = 80°F

Problem Questions and Associated Solutions:

- a. Based on a reference temperature of 73°F, develop the strength-maturity relationship for the following laboratory-cured concrete specimens (Table 2 – students are provided with age and compressive strength and asked to calculate the equivalent age with the maturity method). Regression analysis techniques obtained from prior statistics courses can be implemented to solve this part of the question. Alternatively, the instructor can provide a spreadsheet as a starting point and use the solver to determine the regression constants.

Table 2—Maturity Method Parameters.

Chronological Age (hours)	Maturity, t_e (hours)	Compressive Strength, f_c (psi)
24	24.8 ^a	990
48	49.7	2,010
72	74.5	3,080
169	174.9	4,340
336	347.7	5,000
673	696.5	5,555

Example: ^a Maturity = $\exp(45,000/8.3144 \times (1/(23.3+273) - 1/(22.8+273))) \times 24 \text{ hrs} = 24.8 \text{ hrs}$

Exponential function for the strength-maturity relationship: $S(t_e) = 6159 \text{ psi} \cdot \exp\left(-\left[\frac{52.1 \text{ hrs}}{t_e}\right]^{0.858}\right)$

Exponential function for the strength-maturity relationship: $S(t_e) = 6159 \cdot \exp\left(-\left[\frac{52.1}{t_e}\right]^{0.858}\right)$

- b. Traffic may be allowed onto the bridge deck when a compressive strength of 4000 psi has been reached. Determine the equivalent-age maturity when traffic may be released onto the bridge.

$$4000 = 6159 \cdot \exp\left(-\left[\frac{52.1}{t_e}\right]^{0.858}\right) \quad \text{Solving for } t_e \text{ gives } t_e = 138.7 \text{ hours}$$

Thus, for specimens cured at 73°F, traffic can be allowed onto the bridge deck after the in-place maturity reaches an equivalent age of 138.7 hours (or 5.8 days).

- c. For each of the construction months listed in the problem definition, use the equivalent-age maturity method to determine the chronological concrete age when traffic may be released onto the bridge (graphed in Fig. 10a).

Release forms after the following chronological times have elapsed.

- January placement: Concrete temperature = $(50-32)/1.8 = 10^{\circ}\text{C}$

$$\text{Maturity} = \exp\left(\frac{45,000}{8.3144}\left(\frac{1}{273+22.8} - \frac{1}{273+10}\right)\right) \times \text{Elapsed Time}$$

$$\text{Maturity} = 0.4371 \times \text{Elapsed Time} = 138.7 \text{ hrs. Therefore, elapsed time} = 138.7 / 0.4371 = 317.3 \text{ hrs}$$

- March placement: Elapsed time = $138.7 / 0.6317 = 219.6 \text{ hrs}$
- May placement: Elapsed time = $138.7 / 1.4948 = 92.8 \text{ hrs}$
- August placement: Elapsed time = $138.7 / 2.0642 = 67.2 \text{ hrs}$
- October placement: Elapsed time = $138.7 / 1.2663 = 109.5 \text{ hrs}$

- d. On one graph, plot the strength development versus the chronological age for each of the construction months by using the equivalent-age maturity method (Fig. 10b).

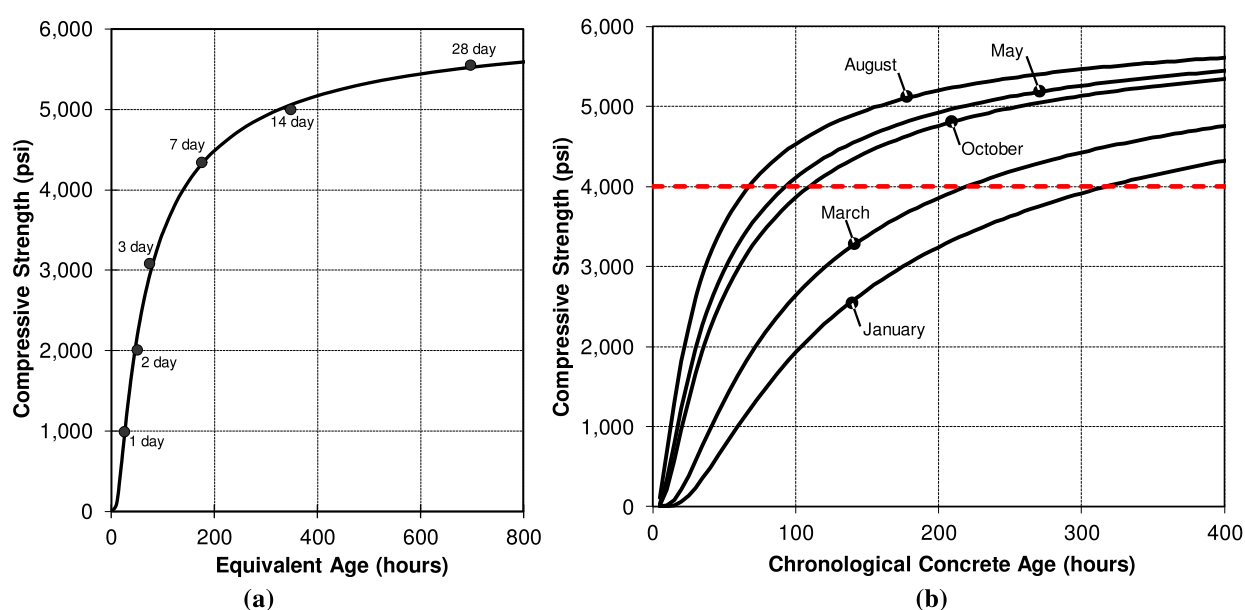


Fig. 10—(a) Strength versus maturity relationship. (b) Strength development versus chronological concrete age for each construction month determined with the equivalent age maturity method.

Orienting teaching of cement hydration principles towards real-world applications—While some students in a typical concrete materials or construction materials class will continue on to graduate studies and perhaps research into the behavior cementitious materials, a large number of the students are going to be more application-oriented as they pursue careers in design or construction. For that reason, it is always a challenge to communicate the practical applications of what may seem to some students to be a rather esoteric and “chemistry-based” study of cement hydration. The following are examples of student exercises and assignments that can help prepare them for real-world applications.

1. Practicing professionals need to know a lot about standard industry documents such as those produced by ACI and ASTM, and those involved in construction need to also be aware of OSHA and ANSI requirements. Bringing such documents into the classroom is a tedious and time-consuming exercise at best and long lectures highlighting various industrial requirements are lethal to a student’s attention span. The challenge is to give students familiarity with the documents that will influence tests, evaluations, and decisions they will be making shortly after graduation. To give the students some familiarity with both the broad scope and the level of detail in industry documents, the instructor can come up with a list of very practical questions for which the answers are not only relevant to the workplace but are embedded in documents such as ASTM C150, ACI 318, and ACI 301. Such exercises are like “Scavenger Hunts,” and it can be entirely appropriate for students to work together in teams as they divide and conquer to complete the instructor’s list of questions. The key is to compose a set of

questions for which the answers can be critical during design or construction, or afterwards in the case of arguments about specification compliance.

2. To augment lectures on the chemistry of portland cement, include not only the requirements of ASTM C150 but also include a typical cement mill test report to show that the same chemical terms and abbreviations used in the classroom and research setting are reported to the consumer of the cement. To drive this connection home the instructor can do the following:
 - a. Acquire a set of concrete specifications (from the facilities or new-construction division of the university – the exercise is particularly meaningful if the specifications are for a campus project familiar to the students).
 - b. Provide student access to ASTM C150 and any other ASTM specifications included by reference for the same university project.
 - c. Provide a cement mill test report and perhaps similar reports for SCMs. Ask the students—individually or in teams—this very practical question “Will the cement (and SCMs) that have been proposed by the concrete producer meet the requirements of the specification for this project?”

This exercise can be made more exciting the more rigorous the project specifications, and the instructor can issue an addendum to the specifications to generate any set of requirements. For example, the specifications (or addendum) may require low-alkali cement, a cement type other than Type I or II, a particular color, particular set time, early-age strength requirements, or low shrinkage. Similarly, in lieu of using an actual cement or SCM mill test report, the instructor can generate a report in which values and test results are altered to cause the students to dig deeper in answering the question.

LESSONS LEARNED

Some thoughts regarding the use of methods suggested in this paper, based on the experience of the authors are as follows, regarding:

The use of physical artifacts and in-class demonstrations: Instructors are cautioned to think carefully about the application of in-class demonstrations. Preparation for the demonstration and successful implementation have been shown to factor into the success of their use. Unsuccessful or interrupted demos reduce student attention and overall learning gains (Sharma et al. 2010). Additionally, an approach in which students merely observe the demonstration does little to increase overall understanding of the topic (Crouch 2004). Instead, students must be actively engaged in the learning process and following discussions. Some suggested methods of transforming instructor demonstrations into active learning techniques include: having students perform the demonstration (perhaps in groups), or at least allowing students to touch/experiment with the product following the demonstration (Hackathorn et al. 2011); asking students to submit handwritten predictions prior to the demonstration (or use an electronic poll system); posing an open-ended question using a worksheet, after which students discuss their observations and whether it met their predictions (Crouch 2004); and asking students to apply information learned from the demo in subsequent homework assignments (Kresta 1998, Hackathorn 2011).

The use of inquiry-based and experiential learning techniques: Use of effective inquiry-based learning projects is often an iterative process, requiring the instructor to think deeply about what objectives are essential for the project and which may be superfluous. For the first few iterations, instructors must also continuously reassess the success or failure of the methods and instructions associated with the project. Instructors may find they are required to give additional instruction in topics not explicitly a part of the course, such as how to perform a literature search and review, basics of good experimental design (using control samples, generating testable hypotheses), how to properly assess and understand data, and elements required for effective communication (how to create an effective graph or table, properly discussing findings (as opposed to simply reporting data)). What students do not know with regards to these elements is often surprising.

In addition, instructor support of more student-led activities is essential. While the instructor’s teaching load may be partially reduced with use of inquiry-based and experiential learning models, instructor load in supporting student learning is typically increased. Instructors must build in opportunities to ‘check-in’ and interact with students, while assessing student learning with sufficient time to early correct identified deficiencies. While some students will happily reach out with questions and to check their understanding of the principles to be learned, many are often either afraid to reach out or unaware that they have not achieved the goals of the projects, until it is too late. In this

way, early intervention by the instructor can prevent potential issues resulting from inquiry-based learning experiences.

The use of reflective papers and focused quizzes: While the frequency of assessment proposed for use of one-minute papers, daily quizzes, etc. may seem high, the following observations were made after five semesters of using this homework/daily quiz model, many of which are consistent with findings reported in literature:

- Student engagement with the material increased, and students are more able to readily participate in in-class activities and discussions. Daily quizzes have also been shown to promote higher-level thinking (Braun and Sellers 2012) and provide immediate feedback to students on their learning progress (Kwan 2011, Connor-Greene 2009).
- With continuous use of daily quizzes, class attendance remained steady throughout the semester. In semesters where quizzes were presented weekly instead of daily noticeable drops in attendance were observed on off-days. Past research has also indicated that daily quizzes are more effective at sustaining student engagement with the material than weekly quizzes (Mawhinney et al. 1971).
- Students interacted more with each other and the instructor before class, comparing and explaining answers, or consulting the instructor for help. This can facilitate study group formation in classes where students are not already familiar with each other.
- Students are less stressed prior to exams, having been assured through quiz questions that they are focused on the most important topics, having an idea how the instructor formats questions, and having already reviewed important material throughout the weeks prior (Kwan 2011). Course fail rates have also been shown to decrease with use of daily quizzes (Braun and Sellers 2011).
- Grading load on instructor is lessened and spread out more evenly. Use of the pass/fail format facilitates rapid grading and removes subjective judgement if graders are employed with the course.
- Benefits to students through the use of daily quizzes have been shown to be independent of instructor skill levels (Kugel 1989).

Despite the obvious gains for students, use of immediate feedback techniques may be somewhat jarring to instructors, who need to be prepared for the eye-opening experience of discovering that images they thought were so clear and communicated so affectively can be grossly misunderstood. This being the case, the instructor may need to grade early assessments liberally, recognizing that the student may truly believe that he or she understands what that image was “supposed” to show. Knowing that they are responsible for understanding images shown in the lecture encourages students to pay more attention to “slide-shows” and to ask more questions when pictures, illustrations, or graphs are shown in class. This experience also teaches the instructor to be more specific when using images in lectures or in reading assignments and can guide later study on the subject, prior to examinations. Finally, any of these techniques can be readily adapted for distance learning either by live presentations or by pre-recorded demonstrations. The authors have used both modes successfully.

CONCLUSIONS AND RECOMMENDATIONS

Civil engineering materials is a field in which the bulk of knowledge hinges on qualitative understanding of chemistry and materials science concepts, rather than on the quantitative analytical techniques most civil engineers are used to and were trained in. Likewise, teaching about cement hydration and civil engineering materials requires use of approaches much different from those employed in many other engineering courses. This paper covers many examples of in-class discussion topics, demonstrations, and information organization approaches, as well as providing simple experimental and learning-centered assessment approaches to effectively transfer cement hydration knowledge to undergraduate students.

Many of the techniques presented herein use analogies that link cement hydration behaviors and properties to concepts that engineering students encounter throughout daily life and are familiar with including coffee fineness, and heat release from hand warming packets. In addition to the use of metaphors to enhance understanding of cement hydration concepts, employment of simple demonstrations and experiments (visuals of space proportions in varying w/c, paste samples demonstrating workability differences, tracking and comparison of heat emission from paste mixtures) can assist in reinforcing many of the key concepts related to cement hydration. Finally, instructors can take advantage of learning-centered assessment approaches to: 1) provide additional efforts to organize the prolific amounts of information through approaches such as concept-mapping, daily quizzes, and one-minute papers,

which can help students differentiate between important topics and extra information; 2) promote staggered learning (rather than pre-test cram sessions); and 3) frequently link the less obvious applications of chemistry-based concepts associated with cement hydration back to its impact on the real-world concrete performance. This can be achieved through use of specifications, industry test reports (such as cement mill sheets), construction anecdotes (such as the need to cast concrete overnight hours to control temperature and hydration rate), and employment of homework assignments such as the maturity method example, in which the impact of hydration time and temperature are linked to in-place strength development and thus the time to open a bridge deck to traffic.

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ACI member **Lisa E. Burris** is an Assistant Professor in the Department of Civil, Environmental, and Geodetic Engineering at the Ohio State University. She received her B.S. and M.S. in Architectural and Civil Engineering, respectively, from Kansas State University, and her Ph.D. in Civil Engineering from the University of Texas at Austin. She is a member of ACI Committees 123 (Research), 232 (Fly Ash in Concrete), 236 (Materials Science of Concrete), and 242 (Alternative Cements).

ACI member **Kenneth C. Hover**, P.E., is Professor and Weiss Presidential Fellow at Cornell University. He is a member of Committees 301 Specification, 305 Hot Weather, 306 Cold Weather, and subcommittee A of 318 Building Code. He was an Army Combat Engineer Officer, project engineer and project manager for Dugan & Meyers Construction, and a partner and manager for THP structural engineers before coming to Cornell. He is an Honorary Member and was ACI President 2010-2012.

ACI Fellow **Anton K. Schindler**, P.E., is the Director of the Highway Research Center and Professor in the Department of Civil Engineering at Auburn University, Alabama. He received his MSE and PhD from the University of Texas at Austin. He is the Chair of ACI Committee 237 (Self-Consolidating Concrete) and former chair of ACI Committee 231 (Properties of Concrete at Early Ages). He received the ACI Wason Medal for Materials Research in 2006 and 2011.

ACI member **Aleksandra Radlińska** is the Chair of the Concrete Research Council and former chair of Committee 123 on Research and Current Developments. She serves as an Editor for the Journal of Construction and Building Materials (Elsevier) and Associate Editor for the ASCE Journal of Materials in Civil Engineering. Her service to the concrete industry was recognized in 2012 with the ACI Young Member Award for Professional Achievement and in 2018, when she was named as an ACI Fellow.

Pedagogical Techniques used to Teach Fresh and Hardened Concrete Properties

Kacie C. D'Alessandro, Andrei Ramniceanu, Jacob D. Henschen, Matt O'Reilly

Synopsis: This paper presents pedagogical techniques used to teach fresh and hardened properties of concrete. Fresh properties of concrete include the evaluation of slump, unit weight, and air content. The hardened properties of concrete include compressive and tensile strengths. Students typically have little to no prior experience working with concrete. Since concrete structures date back to Ancient Rome, many students assume concrete is a basic material that has not changed in centuries, and they do not view concrete as an engineered material. Therefore, their understanding of how concrete is an engineered material and its use is essential. This paper focuses on how both fresh and hardened concrete properties are taught in the classroom to best introduce students to concrete as an engineered material. The pedagogical methods focus on engaging students using experiential education through hands-on laboratory activities, projects, and game-based learning activities. Examples of the pedagogical approaches are presented herein, and they are supported by lessons learned by the authors based on their experience implementing these methods in the classroom.

Keywords: slump, unit weight, air content, compressive strength, tensile strength, active learning, experiential, laboratory, game-based learning

INTRODUCTION

Understanding fresh and hardened concrete properties provides a foundation for students to use concrete in civil engineering applications. Fresh and hardened concrete properties are taught at the undergraduate level in civil engineering materials courses. Since an understanding of concrete material properties is required for design of concrete structures, these properties are also often taught or reviewed in undergraduate reinforced concrete design courses. Prior to taking these undergraduate courses, students often have the preconceived idea that concrete is a basic material. In other words, they do not see concrete as an engineered material. Rather, they sometimes believe modern-day infrastructure is built using concrete like that used by the Ancient Romans (Jahren 2018). Then, when they learn about how material properties can be optimized for different applications, their minds are opened to a new perspective, and they can see concrete as a more complex, engineered material. Understanding fresh and hardened concrete properties is essential to shaping this new perspective.

This paper presents the pedagogical practices used to teach fresh and hardened concrete properties. These techniques include active learning and experiential education through hands-on activities, projects, and games. Specific examples are provided for each approach, and lessons learned are presented to assist instructors interested in implementing these methods.

OVERVIEW OF FRESH AND HARDENED CONCRETE PROPERTIES

Fresh and hardened concrete properties generally include the means used to classify concrete in both the plastic and hardened states. These properties are typically measured using standardized ASTM International procedures. Fresh concrete properties provide a means to evaluate constructability and expected future performance. Hardened concrete properties indicate physical performance as a response to applied force and other physical characteristics. Table 1 includes a list of properties that may be addressed in an undergraduate materials course where concrete is discussed as well as the corresponding ASTM procedures used to evaluate these properties. Some properties are commonly discussed in more detail in an undergraduate course. These properties include workability, air content, compressive strength, tensile strength, static modulus of elasticity, and Poisson's ratio. Other properties may be introduced only briefly. For example, creep and shrinkage may be introduced conceptually as time-dependent properties; however, test methods and the complete mechanism involved in each would likely not be discussed in detail in an introductory undergraduate course. The pedagogical methods presented herein focus on those properties more common to an introductory undergraduate course.

Table 1—Fresh and hardened concrete properties.

Property Type	Property	ASTM International Procedure
Fresh	Workability*	C143/C14CM
		C1611/C1611M
	Air Content*	C173/C173M
		C231/C231M
		C138/C138M
	Unit Weight	C138/C138M
	Temperature	C1064/C1064M
Hardened	Setting Time	C403/C403M
		C191/C191M
	Compressive Strength*	C31/C31M
		C39/C39M
	Splitting Tensile Strength*	C496/C496M
	Flexural Strength of Concrete*	C78/C78M
	Static Modulus of Elasticity*	C469/C469M
	Poisson's Ratio*	
	Creep in Compression	C512/C512
	Shrinkage	C157/C157M

*Properties commonly discussed in more detail in an undergraduate course.

OVERVIEW OF PEDAGOGY

Several active learning and experiential approaches are often used to teach fresh and hardened concrete properties. Active learning approaches engage students in the learning process, allowing students to become learning participants rather than passive observers (Prince 2004), and experiential learning is a type of active learning where students learn by performing an activity (Kolb 2014). Demonstrations and simple hands-on activities are among the simplest active learning approaches. Game-based learning is also a simple and repeatable approach to actively engage students in review of primary concepts and knowledge. Consistent with the Replacement, Amplification, and Transformation (RAT) framework established by Hughes et al. (2006), games are presented herein as an approach of Amplification to classroom instruction. In other words, games in this context supplement instruction and encourage productive learning, but they do not replace or significantly transform the learning process. Experiments and hands-on laboratory activities can also be used to supplement lecture material with potential to serve as an experiential learning mechanism (Abdulwahed 2009).

Although project-based learning is more complex to implement, it has potential to challenge students through creative applications of knowledge beyond rote memorization (Prince and Felder 2006). Projects can improve students' conceptual understanding and provide a mechanism to develop professional skills. Projects can also incorporate elements of collaborative learning when completed in groups. Collaborative learning takes place when students work in groups (Prince 2004), and this type of learning has several advantages including improvements in teaming abilities, academic achievement, and student attitudes. One project described herein also includes elements of entrepreneurial-minded learning (EML), where students are encouraged to develop creative solutions and consider stakeholders. Not only does EML prepare students for real-world problems, but it can also positively impact their “motivation to succeed in the engineering field” (Desing 2022).

The learn-before-label approach is also described as an experiential learning technique that implements elements of reflection and a synthesis of ideas. Many pedagogical techniques rely on a concept first being explained or demonstrated by the instructor prior to the students applying it themselves (Drew 2023). In the “learn-before-label” approach, however, students are led to discover a concept themselves in a hands-on environment prior to discussing it in a classroom setting.

Regular quizzing may also be used in combination with other teaching approaches to address information overload and to encourage out-of-class study. More detailed information on the background of specific pedagogical approaches is provided in the first paper of this ACI Special Publication series (Swenty et al. 2023).

PEDAGOGICAL APPROACHES

The authors use active learning methods and experiential education to promote engagement, discovery, and critical thinking. The specific pedagogical approaches presented in this paper include demonstrations, experiments, games, and competitions. Additionally, regular quizzing is included as a method used to address information overload in an information-heavy materials course.

Laboratory demonstrations and experiments

Laboratory experiments and demonstrations are valuable experiential opportunities. Various approaches to laboratory experimentation are presented herein, showcasing increasing levels of complexity.

Videos and demonstrations—When access to equipment is limited, videos and demonstrations can be used to illustrate fresh and hardened concrete properties. Videos can be obtained through simple internet searches, and they can be shown in class to include discussion and additional instructor explanations. If a construction site is nearby, students can be taken to the site to observe the process of mixing concrete and to learn about the tests used to determine fresh concrete properties and preparing samples to determine hardened concrete properties. Demonstrations of hardened concrete property tests could be implemented using premade samples. In fact, testing premade samples can be a fun way to introduce concrete to students by demonstrating its advantageous compressive strength and brittle failure mechanism. These samples could be made in advance by the instructor, a lab technician, or a student. They could also include left-over specimens from a research project.

When possible, first-hand demonstrations that involve students are preferred. At some schools, a dedicated laboratory time is possible to allow significant firsthand involvement of students. However, when this is not possible, laboratory experiments can be integrated into regular class periods. In doing so, concrete can be mixed with students to demonstrate fresh properties of concrete. For example, in a class without a dedicated lab period, two class periods are used to mix conventional concrete and a nonproprietary ultra-high-performance concrete (UHPC), showcasing the difference in fresh concrete properties in each. Prior to the mix sessions, students meet in the classroom to discuss concrete mixing and test procedures for common properties, including slump, air content, compressive strength, and tensile strength. Materials are batched by the instructor in advance of the class, and the lab is equipped with all tools and materials. For each mixture, fresh concrete properties are tested using standard procedures and typical modified standards for UHPC. Slump, unit weight, and air content are measured for the conventional concrete mix. Flow is measured for UHPC instead of slump. Under supervision of the instructor, students complete all procedures and tests. Students also prepare specimens to quantify hardened concrete properties and to learn proper filling and tamping procedures for specimen preparation in the process. These specimens are later used to demonstrate hardened concrete properties including compressive strength and tensile strength in another class session. With more limited time, an instructor could focus solely on conventional concrete thereby reducing the number of class periods required for mixing and testing.

The aforementioned activities were completed during a 75-minute class period with a maximum of 16 students. Although the class was divided into two groups of eight students for mixing and placement, smaller groups of four students working together on a single mix would be preferred in the future to better engage students. With many students collaborating, it was inevitable that some would be less involved. Therefore, smaller mixing groups are preferred.

Experiments and sequential learning modules—When consistent access to a laboratory is possible, a more traditional lecture-before-lab approach can be used to first introduce students to a topic before completing an experiment related to the topic. As an example, four primary modules can be taught in this type of course; the lecture portion of the class includes 1) structure of materials, 2) properties of materials, 3) processing of materials, and 4) performance of materials. In this pattern, the sequence of topics related to concrete includes 1) aggregates, 2) portland cement, 3) admixtures, and 4) portland cement concrete proportioning. The primary goals of this approach are for the students to understand the relationships between the different components of portland cement concrete and to develop an understanding of the weight/volume relationships that govern concrete proportioning. In turn, these activities also address fresh and hardened concrete properties as students use them as a means of comparison.

In this sequential module method, students complete experiments throughout the series that lead to mixing and testing their own concrete mix design to determine fresh and hardened concrete properties. The sequence is introduced by providing a general overview of hydraulic concrete starting with a brief history, general composition, reasons for its success, limitations, its impact on society and the world at large, as well as current and anticipated directions in research and practice. Each topic is then introduced and, where appropriate, example problems are presented. These examples include calculating percent moisture content, dry-rodded unit weight, specific gravity, and percent voids between aggregates. Examples of concrete proportioning through the absolute volume method per ACI Committee 211 (2022) are also presented with particular focus on adjusting the water content as a function of the aggregate moisture content and percent absorption. The students are expected to complete similar problems in-class and for graded homework. The laboratory component is synchronized with the lectures, meaning that the students perform the corresponding laboratory exercise the same week the topic is covered. The modular structure is summarized in Table 2.

Table 2—Sample modular structure for fresh and hardened concrete properties.

Module Topic	No. Lectures	Corresponding Laboratory Components
Aggregates	3	1. Specific gravity / absorption / void analysis 2. Sieve analysis
Admixtures	1	1. Concrete mixture design 2. Proportion concrete, fresh concrete properties, and casting hardened properties specimens
Portland Cement	1	
Concrete Proportioning	2	
Concrete Durability and Testing	1	1. Compressive strength at 7 days 2. Compressive strength at 28 days, third point bending

The laboratory experiments are performed in groups of two or three students. In the Aggregates module, the students are provided with aggregate samples consisting of #57 and #67 locally sourced limestone. They are not provided with the classification, but rather are expected to identify and classify the samples based on their own test results. The test results are then used in the concrete proportioning lab.

For the Concrete Proportioning module, the students are provided with a variety of cases (Table 3). After each group of students selects a case, they proportion an appropriate mixture using the absolute volume proportioning method as outlined by the ACI PRC-211 Guide (2022) and then scale it to 1.5 ft³. They are expected to mix the concrete mixture in a traditional gravity drum mixer, perform a slump test, determine air content using a pressure meter and determine the unit weight. Each group then casts three 4-in. diameter × 8-in. tall cylinders and an unreinforced 4 × 6 × 36-in. beam. The cylinders are tested in compression at 7 and 28 days, and the beam is tested in third point bending at 28 days. The various cases (Table 3) provide the students with the opportunity to use admixtures, such as air entrainers and superplasticizers, and to observe a wide range of different concretes.

Table 3—Cases for concrete mix design.

Case	Description
1	A reinforced concrete beam located in a parking garage. The reinforcing steel will be more than 4 in. apart. The engineer requires that the mix have a 28-day compressive strength of 4,500 psi. The engineer has obtained historical data from a previous 5,000 psi mix that showed a standard deviation $S = 465$ psi obtained from 20 samples.
2	A sidewalk replacement project in Lexington, VA. The sidewalks will be at least 4 in. thick. The city has requested that fiber reinforcing be used in lieu of conventional reinforcing steel. The sidewalks will only have to support pedestrian loads. The engineer has specified a minimum compressive strength of 3,000 psi at 28 days. There is no historical data from previous mixtures.
3	A foundation wall at a loading dock in Key West, FL. The wall will be relatively thin in many locations (as low as 6 in. thick). The steel will be relatively congested. The engineer has required a compressive strength of 6,500 psi at 28 days. The ocean water at that location has a sulfate concentration of 5,500 ppm. The standard deviation was reported as $S = 320$ psi from 35 samples.
4	A bridge deck slab located in Duluth, MN. The deck will be 7.5 in. thick with steel reinforcing located at 5 in. on center in both directions. To receive Federal funding, the deck concrete must qualify as “high performance.” Therefore, the engineer has specified a compressive strength of 5,000 psi at 28 days. The standard deviation was reported as $S = 560$ psi from 10 samples.

Reports are required throughout the project duration to develop professional communication skills. The students are expected to write comprehensive laboratory reports for the specific gravity/absorption/void analysis and sieve analysis experiments in the Aggregate module. The concrete mixture design, concrete proportioning, and 7-day break laboratories require a memo with a summary of the results. Following the 28-day compressive strength and third point bending laboratory, the students are expected to complete another comprehensive report that incorporates the mixture design and fresh and hardened concrete properties.

These activities were completed with a maximum class size of about 10 students with one instructor. Additional laboratory assistance is recommended for significantly larger class sizes.

ACI certification—A great way to expose students to the full range of plastic concrete properties is to provide opportunities for students to practice the skills necessary to obtain ACI Grade I Field Certification. In this

approach, every student in class is required to undergo the performance portion of field certification in lab, with the option of taking the written exam and obtaining certification for those who wish to pursue it. The various plastic concrete tests are demonstrated in the weeks leading up to the performance exam; students are also required to perform slump, temperature, and unit weight tests as well as make concrete test cylinders in groups as part of the lab tests prior to the performance exam. Concrete is provided in the lab for students to practice tests at their convenience. Overdosing the practice concrete with a hydration stabilizer ensures it does not set and requires minimal water additions and remixing every few days to maintain a proper workability. A similar approach could be taken to prepare students for the ACI Concrete Strength Testing Technician exams to address testing hardened concrete properties.

Regular quizzing

Weekly quizzes can be incorporated into materials courses to overcome the challenge of information overload. This approach of regular quizzing was used throughout the course, including topics of fresh and hardened concrete properties. Weekly quiz content was derived based on class sessions from the previous week and recent reading assignments. For example, when laboratory demonstrations and activities were used to teach fresh and hardened concrete properties, quiz questions specifically addressed these activities as a form of reflective learning.

In one case, the weekly quizzes were administered at the start of class time, and students were allowed 5 to 7 minutes to complete the quiz. All quiz questions were short-response or multiple choice, and the correct answers were discussed immediately following collection to provide immediate feedback to students. Unfortunately, it also meant students were not permitted to make-up a quiz after it was discussed in class. In a subsequent course offering, quizzes were administered using the university's online learning management system (LMS) to allow more flexibility in completing the quizzes. Answers were available immediately following the due date, and many questions were intentionally incorporated into the next class period. Due to more flexibility in quiz completion using the LMS, some essay-response questions were added as intentional test preparation. In both cases, students were permitted to use their notes to complete the quizzes. Resultantly, the quizzes encouraged students to maintain an organized notebook and complete reading assignments regularly. Reading assignments were accompanied with guided reading prompts to help students identify key concepts, and some quiz questions were derived directly from the reading prompts. With weekly quizzes, students could digest smaller chunks of information within a shorter timeframe via several lower-stakes assignments prior to a comprehensive high-stakes test.

Games

Game-based learning can be used to review concepts and facts related to course topics. A game board was developed using a PowerPoint template to format questions and answers. Questions for the review game were organized into categories like a Jeopardy game. The format of the game board illustrated in Fig. 1 shows several possible topic headings to represent content related to fresh and hardened concrete properties. Some headings are represented by song titles or a play on words to add an element of fun to the game board. The "Cement Supplements" category addresses supplementary cementitious materials, and "Plastic Passion" includes questions on plastic concrete properties. The "Under Pressure" category is for questions related to compression, "The Tension Dimension" addresses tensile strength of concrete, and "Time after Time" is for time dependent properties. Questions and answers were input by the instructor into the template slides (Fig. 2).

Cement Supplements	Plastic Passion	Under Pressure	The Tension Dimension	Time after Time
<u>10</u>	<u>10</u>	<u>10</u>	<u>10</u>	<u>10</u>
<u>20</u>	<u>20</u>	<u>20</u>	<u>20</u>	<u>20</u>
<u>30</u>	<u>30</u>	<u>30</u>	<u>30</u>	<u>30</u>
<u>40</u>	<u>40</u>	<u>40</u>	<u>40</u>	<u>40</u>
<u>50</u>	<u>50</u>	<u>50</u>	<u>50</u>	<u>50</u>

Fig. 1—Sample game board to review course topics.

Question How does tensile strength of concrete generally compare to compressive strength of concrete? (% - percentage) The Tension Dimension 10	Answer Tensile strength is about 10% of the compressive strength. The Tension Dimension 10
Question Under what conditions will concrete creep? Time after Time 10	Answer Sustained loading Long-term applied stress leads to creep. Time after Time 10

Fig. 2—Sample questions and corresponding answers.

Game play in class was arranged for simplicity and included small teams of 2 to 3 students. The simplest way for students to indicate they wished to answer the questions was to raise hands, and the instructor would select the team that raised a hand first. Buzzers were also used one time; however, it was more difficult to differentiate buzzers as compared to raised hands. Once the first team to raise their hand was identified, they answered the question. If correct, they were awarded the allotted points. If incorrect, the next team in line was offered a chance to earn the points. This continued until a team answered the question correctly or until all teams had been given a chance to respond. The instructor only added points for correct answers and did not subtract points for incorrect responses; however, subtraction could also be implemented. The game was used with a maximum class size of 16 students.