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Digital Standards Education Modules for Innovation and Sustainability of Concrete Infrastructure

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Digital Standards Education Modules for Innovation and Sustainability of Concrete Infrastructure

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Abstract

The goal of this project was to combine standards education in concrete and cementitious materials with future and emerging technologies to prepare students for sustainability and resilience of the built environment. With mounting costs to repair America's infrastructure, from both age and natural disasters, coupled with increasing pressures for environmental and social sustainability of concrete manufacture and construction, all aspects of the industry will undoubtedly need to adapt in the future. This project developed self-directed digital standards education modules for students to better understand the need for standardization in concrete construction, to be prepared to adapt to future performance-based standards for cement-based materials, and to recognize and interpret how to implement new technologies that do not fit within current standards. The content was developed through an open-access Canvas website. During development, modules were piloted to undergraduate students during the Fall 2021 and Fall 2022 semesters to gain student feedback and the final completed modules were piloted to undergraduate students during the Spring 2023 semester. The findings indicated the effectiveness of the modules in educating students about the significance and role of standards in the concrete industry. Across all four modules, self-assessment results showed a notable increase in students' knowledge, as evidenced by the higher percentage of students selecting "strongly agree" and "agree" on Likert scale questionnaires. Overall, 93% to 100% of students agreed that the modules provided new and useful information about standards and increase knowledge of standards in the concrete industry.

1. Introduction

Civil infrastructure in the United States faces a severe economic hurdle. The latest "Infrastructure Report Card" from the American Society of Civil Engineers (ASCE) grades America's infrastructure at a C– [1], and the ASCE reports that failure to invest in infrastructure now and in the coming years will result in a loss of $10 trillion to the U.S. GDP by 2039 [2]. The National Association of Corrosion Engineers (NACE International) reports that corrosion-related infrastructure damage alone incurs a global cost of $2.5 trillion [3]. In addition, economic losses caused by natural disasters have been increasing due to climate change and the increased exposure of densely populated areas to extreme weather events [4–8]. To better resist these hazards, civil infrastructure requires a paradigm shift in the design for resiliency [9], and new and emerging technologies will play a key role in how infrastructure resiliency is achieved [10]. Inevitably, this means that changes to standards and building codes will be required [11,12], which is a multiyear process involving consensus of hundreds to thousands of interested stakeholders [13,14].

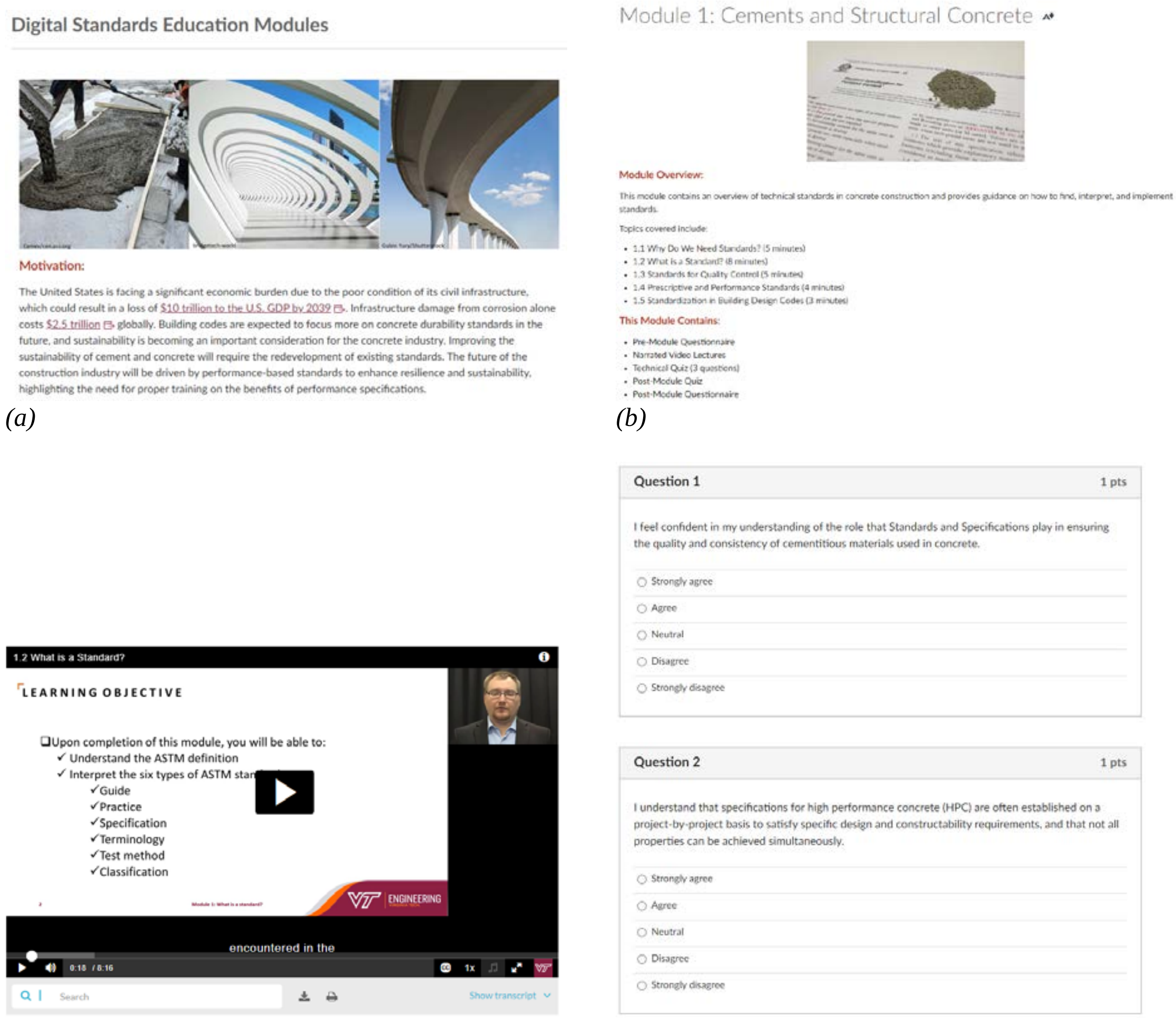
Portland cement concrete is probably the most vital material in civil infrastructure, since it is used in buildings, bridges, roads, dams, ports, tunnels, *etc*. Portland cement, which forms the binding component of concrete when mixed with water, has a worldwide production of over 4 billion tons per year [15], with a 20% estimated increase in production by 2050 [16]. An estimated 30 billion tons of concrete is produced annually [17], which is significantly greater than the production of steel and wood combined. Because of the volume of cement and concrete consumed and the cement production process, portland cement manufacturing is the third largest producer of CO_2, accounting for 5% to 8% of global anthropogenic CO_2 [18–20]. This industry has recognized this significant carbon footprint and has developed roadmaps to carbon neutrality by 2050 [21], which means that cement and concrete standards will need to evolve with trends in sustainability [22,23]. In addition, many current cement and concrete standards are prescriptive, while an anticipated future trend is a greater integration of concrete durability standards within a performance-based framework [23–27].

Therefore, it is clear that standards and codes in cement, concrete, and building industries are expected to evolve – perhaps dramatically – in the coming years and decades. In anticipation, undergraduate and graduate students as well as other interested stakeholders should be educated in the use of standards in these industries but should also be informed of the predicted changes to be able to adapt with future developments. This manuscript reports on the development and implementation of digital education modules for standards for concrete infrastructure.

2. Development of the Modules

The modules were developed with a Canvas framework and published as open access: https://canvas.vt.edu/courses/123210. Figure 1 illustrates typical screen capture images of the Canvas website. Modules were developed in four thematic areas: (1) Cements and Structural Concrete, (2) High Performance Concrete, (3) Cement and Concrete Sustainability, and (4) Future of Concrete Design and Manufacture. The online interactive learning modules were designed for vertical integration in relevant thematic course groupings at the undergraduate and graduate levels to achieve an increasing progression of student knowledge. As such, any student enrolled at Virginia Tech was able to self-register and complete the learning modules at their own pace. The modules were made available to students as optional activities in their respective undergraduate or graduate courses, with the added incentive of earning extra credit towards their final grade. The amount of extra credit earned varied based on the number of modules completed.

After the completion of the modules, students could expect to be: (1) broadly educated on the societal role of standards and standards development; (2) provided with the knowledge necessary to apply cement and concrete standards to ensure the necessary quality and safety attributes of concrete in the built environment; (3) appreciative of standards as constraints and drivers for innovation in future concrete construction; and (4) knowledgeable about and experienced with the societal role of standards and standards development, the importance and necessity of quality and safety attributes of concrete in the built environment, and the synergistic interrelationship between research, innovation, and standardization in modern and future concrete construction.



(a) (b) (c) (d)

Figure 1. Screen capture images of the Digital Standards Education Modules Canvas site: (a) landing page, (b) Module 1 introduction, (c) typical narrated video lecture, and (d) example questionnaire.

2.1. Cements and Structural Concrete Module

The entry-level Cements and Structural Concrete Module is aimed at junior and senior undergraduates and provides an overview of technical standards and the standardization process. Five submodules were created, which culminate in a student-led exercise based on the knowledge gained. The five submodules are: Why Do We Need Standards?, What is a Standard?, Standards for Quality Control, Prescriptive and Performance Standards, and Standardization in Building Design Codes. This content includes narrated lectures, lecture slides, and a transcript of the lectures and covers topics of the history of standards, modern standards developing organizations, types of standards from ASTM International, examples of common quality control standards used in the concrete industry, prescriptive *vs.* performance standards, and the difference between standards and building design codes. To assess student learning, a Likert scale questionnaire is given before and after completing the module and a technical assessment quiz is given after completing the module. The Likert scale questions are given in Table 1.

Module 1 ends with a student-led case study. A short presentation introduces the topic and concept and then it is the student's responsibility to complete the activity. In short, the activity requires the students to critically think about the construction of the world's tallest building, the Burj Khalifa. During construction, the Burj Khalifa broke a number of construction records and utilized a number of novel materials and approaches, not all of which had been standardized. To complete the activity, the student researches the construction of the Burj Khalifa using online resources and then brainstorms and discusses the challenges presented by constructing a supertall structure and how engineers were able to accommodate materials and designs that may not have been standardized.

2.2. High Performance Concrete Module

The second module, which centers on High Performance Concrete, targets junior and senior undergraduate students while also providing enough technical depth to cater to entry-level graduate students. This module provides an overview of a various special topics in high performance concrete (HPC), which are concretes that are specifically designed to meet specific performance criteria that may not be achieved by conventional or "general purpose" concrete. Eight submodules were created: Physical and Material Characteristics of HPC, High Strength Concrete, High Early Strength Concrete, High Durability Concrete, Ultra High Performance Concrete, Self-Consolidating Concrete, Fiber-Reinforced Concrete, and High Performance Reinforcing Bars. This content includes narrated lectures, lecture slides, and a transcript of the lectures. To assess student learning, a Likert scale questionnaire is given before and after completing the module and a technical assessment quiz is given after completing the module. The Likert scale questions are given in Table 1.

2.3. Cement and Concrete Sustainability Module

The third module on Cement and Concrete Sustainability is aimed at senior undergraduate and graduate students and provides a presentation on sustainability and the future outlook on standards for sustainable concrete. Two submodules were created, which culminate in a student-led exercise based on the knowledge gained. The two submodules are: Cement Production and Carbon Dioxide and Standards for Low Carbon Dioxide Concrete. This content includes narrated lectures, lecture slides, and a transcript of the lectures and cover topics of why cement production produces so much CO_2, why concrete has a relatively large carbon footprint, current industry-led initiatives on how to reduce or eliminate the carbon footprint of concrete, current and future options to reduce the carbon footprint of concrete, and a perspective on how future standards can impact the carbon footprint of concrete. To assess student learning, a Likert scale questionnaire is given before and after completing the module and a technical assessment quiz is given after completing the module. The Likert scale questions are given in Table 1.

Module 1 ends with a student-led activity. The first activity requires students to access an online tool from Circular Ecology [28] to calculate the carbon footprint of concrete by considering the mix design, transport, construction, and reinforcing steel. Through a guided procedure, the students first use the Circular Ecology tool to calculate the carbon footprint for various concrete mixes and then compare the results to discuss how such tools or data could be used in a standard or building design code. The second activity requires the students to review at least one industry roadmap to achieve carbon neutrality in the cement and concrete industries. Links to the two roadmaps are provided from the Global Cement and Concrete Association [21] and the Portland Cement Association [29]. Following the review of one or both roadmaps, students are encouraged to share their perspective on the feasibility of the roadmap's objectives and the role of standards and building design codes in attaining those objectives.

2.4. Future of Concrete Design and Manufacture Module

Given that the future of concrete design and manufacturing is evolving rapidly, the PIs realized that a static set of lectures would be outdated shortly after completion. Therefore, Module 4 was redeveloped from its original proposal, transforming into a student-led project. The concept of Module 4 is for the students to explore the latest data and newest information about future concrete technology, considering such topics as 3D printing, structural health monitoring, building information modeling, the use of drones or digital twins during concrete construction, production of carbon negative concrete, or extraterrestrial concrete construction on the Moon or Mars. Module 4 is intended for senior undergraduate and graduate students, particularly as an activity to engage and excite students about the latest and greatest advancements in concrete design, manufacturing, and technology.

For this specific iteration of Module 4, the decision to focus on 3D printing of concrete in the student-led exercise was influenced by several factors: 1) many students are very interested in the topic and the PIs have fielded many questions about it during class; 2) it is a current "hot topic" in concrete technology; and 3) it aligns with the objectives of the digital modules to discuss the context of standards, since many researchers and practitioners have clearly identified the need for standards and building design codes for 3D printed concrete structures [30–32]. For the activity, the students are required to implement the knowledge gained in Modules 1, 2, and 3 to research the current and future outlook in 3D-printed concrete structures. The deliverable for the activity is a presentation of at least five lecture slides that discuss the benefits, applications, disadvantages, regulatory limitations, and need for standardization for 3D-printed concrete structures. To equip students with a foundation for their own research, an introductory lecture on 3D printed concrete was provided at the beginning of Module 4. However, it was the students' responsibility to explore the literature and news articles independently and prepare their slides based on their own understanding of 3D printed concrete. To assess student learning, a Likert scale questionnaire is given before and after completing the module, the questions of which are given in Table 1.

3. Results and Discussion

The content from all four modules has been piloted to a total of 323 undergraduate and graduate students at Virginia Tech. The term and number of students that completed the activities is shown in Table 2. Piloting in Fall 2021 and Fall 2022 included senior undergraduate students and first-year graduate students. Piloting in Spring 2023 included junior and senior undergraduate students. In Spring 2023, not all undergraduate students completed all modules.

Table 1. Likert Scale Questions Used in Modules 1, 2, 3, and 4

Module	Likert Scale (Strongly Agree to Strongly Disagree) Questions
1. Cements and Structural Concrete	• I know what a "standard" is. • I understand why standards are needed in civil engineering. • I understand how standards are used for concrete materials and construction quality control. • I know the difference between prescriptive standards and performance standards.
2. High Performance Concrete	• I feel confident in my understanding of the role that standards and specifications play in ensuring the quality and consistency of cementitious materials used in concrete. • I understand that specifications for high performance concrete are often established on a project-by-project basis to satisfy specific design and constructability requirements, and that not all properties can be achieved simultaneously. • I understand the importance of proper selection, optimization, and batching aggregates, supplementary cementitious materials, and chemical admixtures in the behavior of high performance concrete. • I understand the need for research and testing to advance the capabilities and properties of high performance concrete, while at the same time the need for standards and specifications to ensure its quality, consistency, and reliability in different applications and environments.
3. Cement and Concrete Sustainability	• I know how CO_2 is produced during cement production and how this relates to the carbon footprint of concrete. • I understand how the carbon footprint of concrete can be reduced. • I understand the role that standards play, either now or in the future, in considering concrete with low carbon footprints.
4. Future of Concrete Design and Manufacture	• In general terms, I am confident that I know what "additive manufacturing" or "3D printing" is. • I am confident in my ability to describe the process of 3D printing of concrete and other cement-based materials. • I can effectively communicate the limitations of 3D printing of concrete with regard to the need for standardization and/or building design code provisions.

Table 2. Details of Piloting the Modules

Term	Module Piloted	Number of Undergraduate Students	Number of Graduate Students
Fall 2021	1	32	7
Fall 2022	1	41	5
	3	41	5
Spring 2023	1	59	0
	2	54	0
	3	54	0
	4	25	0

3.1. Piloting Partial Modules in Fall 2021

The draft content for Module 1 was piloted in Fall 2021 to a class of 39 students that included 32 senior undergraduates and 7 first-year graduate students. The course topic was on concrete materials. The feedback gained from this semester was used to improve the content and delivery of Module 1. The capstone activity for Module 1 was not implemented until Fall 2022. A Likert scale questionnaire was not developed for piloting in Fall 2021, although the students were asked the question "How are standards used in the concrete industry and why do we need standards?" before and after completing the draft Module 1 content. The students were also asked to reflect if and why their answer changed after completing the draft Module 1 content.

Of the 32 senior undergraduate students: 18/32 (56%) reported that their answer to the question definitely changed and that the draft Module 1 content was helpful, 6/32 (19%) reported that their answer only changed slightly but that the content was still useful, 7/32 (22%) reported that their answer to the question did not change but that they found the content helpful to remind them about the importance of standards, and 1/32 (3%) found that their answer to the question did not change and that the content in Module 1 was not useful. Therefore, 31/32 (97%) of senior undergraduate students reported that the draft Module 1 content either informed them or reminded them about the importance of standards. As the content for Module 1 is intended for junior and senior undergraduate students, the draft Module 1 content was validated as appropriate for these students.

Of the 7 first-year graduate students, 1/7 (14%) reported that their answer to the question changed significantly and 6/7 (86%) reported that their general answer to the question did not change but that they found the content helpful to remind them about the importance of standards. As the content for Module 1 is intended for junior and senior undergraduate students, it was not surprising that the majority of first-year graduate students did not find that the Module 1 content changed their understanding of standards in the concrete industry, since they were already aware of the importance of standards from other coursework, from on-the-job training and experience, and/or from their graduate research.

3.2. Piloting Partial Modules in Fall 2022

The final versions of Modules 1 and 3, including the capstone activities, were piloted in Fall 2022 to a class of 46 students that included 41 senior undergraduates and 5 first-year graduate students. The course topic was on concrete materials. The feedback gained from this semester was used to improve the questionnaire and technical quiz. A Likert scale questionnaire was not developed for piloting in Fall 2022, although the students were asked the questions "What is a standard? What is the purpose of a standard? Why do civil engineers specify standards in designs?" before and after completing Module 1. The students were also asked to reflect if and why their answer changed after completing Module 1. A technical quiz was given after the completion of Module 1 to assess student comprehension of the content. For Module 3, the students were asked questions to consider their knowledge of the topic, but they were not asked to reflect on those answers after completing the module. However, the students were asked for feedback on the usefulness of Module 3 in improving their understanding of sustainability in concrete materials.

Of the 41 senior undergraduate students: 13/41 (32%) reported that their answer to the questions definitely changed, 17/41 (41%) reported that their answer only changed slightly but that the content was still useful and/or that the content refined their answers, and 11/41 (22%) reported that their answer to the question did not change but that they found the content helpful to remind them about the importance of standards. None of the students reported that Module 1 was unhelpful, and all of the undergraduate students did provide feedback they thought that the content of Module 1 was helpful.

Of the 5 first-year graduate students, 4/5 (80%) reported that their answer to the questions did change and that the module updated or reminded them about standards and 1/5 (20%) reported that their answer to the questions did not change. All graduate students provided positive feedback, expressing that the content of Module 1 was beneficial in aiding their understanding of the role of standards in concrete construction.

After the completion of Module 1, the students were given a technical quiz to assess student comprehension of the content. The quiz questions were all multiple choice, and the students had the ability to access Module 1 during the quiz. The 44 total students scored an average of 94% on the four technical questions, so the level of difficulty of the questions were deemed appropriate for the module.

For Module 3, 36/39 (92%) of senior undergraduate students and 5/5 (100%) of first-year graduate students found the content helpful to understand sustainability in concrete materials. A number of students specifically highlighted that at least one of the capstone activities was enjoyable or informative. As the content for Module 3 is intended for senior undergraduate and graduate students, the Module 3 was validated as appropriate for these students.

3.3. Piloting All Modules in Spring 2023

The final versions of Modules 1, 2, 3, and 4 were piloted in Spring 2023 to 59 junior and senior undergraduate students in two courses, although not all students completed all modules. The course topics were on civil engineering materials and reinforced concrete design. The Likert scale questions in Table 1 were implemented for this session. Technical quizzes were given after the completion of Modules 1, 2, and 3 to assess student comprehension of the content. Since the students were allowed an unlimited number of submissions on the quizzes in order to learn from any incorrect answers, all students received 100% on the quizzes. After completing each module, the students were also given Likert scale questions to assess their impressions of the effectiveness of the module: “The module provided me with useful information about standards that I did not know before” and “Overall, I found this module to be helpful in increasing my knowledge of standards related to cements and structural concrete.”

For the Module 1 results, the Likert scale answers for “Strongly agree” increased for all four questions (Table 3). In fact, after completing Module 1, all students answered “Strongly agree” or “Agree” for all four questions, while a few students answered “Neutral” or “Disagree” before completing Module 1. From the results, it is evident that many junior and senior civil engineering students are already confident in their knowledge of standards and that Module 1 served to increase that confidence. The most dramatic impact was for differentiating prescriptive and performance standards; before Module 1, more than half of the students reported not knowing the difference, but after Module 1 all students reported “Strongly agree” or “Agree.”

Table 3. Percent of Student Responses to the Module 1 Likert Scale Questions

Question	Likert Scale	Before	After
"I know what a standard is."	Strongly agree	36%	78%
	Agree	57%	22%
	Neutral	7%	0%
	Disagree	0%	0%
	Strongly disagree	0%	0%
"I understand why standards are needed in civil engineering."	Strongly agree	57%	86%
	Agree	41%	14%
	Neutral	2%	0%
	Disagree	0%	0%
	Strongly disagree	0%	0%
"I understand how standards are used for concrete materials and construction quality control."	Strongly agree	36%	66%
	Agree	43%	34%
	Neutral	15%	0%
	Disagree	7%	0%
	Strongly disagree	0%	0%
"I know the difference between prescriptive standards and performance standards."	Strongly agree	25%	68%
	Agree	21%	32%
	Neutral	26%	0%
	Disagree	28%	0%
	Strongly disagree	0%	0%

For the Module 2 results, the Likert scale answers for "Strongly agree" increased for all four questions (Table 4). It is evident that, before completing Module 2, a large percentage of students were not confident in their knowledge of high performance concrete, but after completing Module 2, 98% to 100% of students answered "Strongly agree" or "Agree" for all four questions, with more than 50% answering "Strongly agree."

For the Module 3 results, the Likert scale answers for "Strongly agree" increased for all three questions (Table 5); more than 70% of responses for "Strongly agree" after module completion while 17% to 22% of students had that response before Module 3. This suggests that Module 3 was very effective at educating students on the importance of the carbon footprint of concrete and how standards will impact the future of concrete sustainability.

Table 4. Percent of Student Responses to the Module 2 Likert Scale Questions

Question	Likert Scale	Before	After
"I feel confident in my understanding of the role that standards and specifications play in ensuring the quality and consistency of cementitious materials used in concrete."	Strongly agree	21%	57%
	Agree	41%	43%
	Neutral	34%	0%
	Disagree	3%	0%
	Strongly disagree	0%	0%
"I understand that specifications for high performance concrete are often established on a project-by-project basis to satisfy specific design and constructability requirements, and that not all properties can be achieved simultaneously."	Strongly agree	0%	63%
	Agree	38%	35%
	Neutral	29%	2%
	Disagree	14%	0%
	Strongly disagree	0%	0%
"I understand the importance of proper selection, optimization, and batching aggregates, supplementary cementitious materials, and chemical admixtures in the behavior of high performance concrete."	Strongly agree	29%	65%
	Agree	41%	33%
	Neutral	26%	2%
	Disagree	3%	0%
	Strongly disagree	0%	0%
"I understand the need for research and testing to advance the capabilities and properties of high performance concrete, while at the same time the need for standards and specifications to ensure its quality, consistency, and reliability in different applications and environments."	Strongly agree	29%	63%
	Agree	48%	37%
	Neutral	19%	0%
	Disagree	3%	0%
	Strongly disagree	0%	0%

Table 5. Percent of Student Responses to the Module 3 Likert Scale Questions

Question	Likert Scale	Before	After
"I know how CO_2 is produced during cement production and how this relates to the carbon footprint of concrete."	Strongly agree	22%	76%
	Agree	33%	20%
	Neutral	37%	4%
	Disagree	7%	0%
	Strongly disagree	0%	0%
"I understand how the carbon footprint of concrete can be reduced."	Strongly agree	17%	73%
	Agree	30%	24%
	Neutral	33%	4%
	Disagree	19%	0%
	Strongly disagree	2%	0%
"I understand the role that standards play, either now or in the future, in considering concrete with low carbon footprints."	Strongly agree	22%	75%
	Agree	41%	22%
	Neutral	30%	4%
	Disagree	6%	0%
	Strongly disagree	2%	0%

For the Module 4 results, the Likert scale answers for "Strongly agree" nearly quadrupled after completing the module (Table 6). While a majority of students responded that they knew what 3D printing was in general terms before Module 4, it is evident that they were not familiar with 3D printing of concrete and why standards are important. After completing Module 4, all students responded with "Strongly agree" or "Agree" for all three questions, indicating that Module 4 was very effective at educating students about the need for standardization and building codes with 3D-printed concrete structures.

Table 7 shows the summary of the Likert scale questions for students to assess the effectiveness of the four modules. Nearly all students (93% to 96%) found Modules 1, 2, and 3 and all students (100%) found Module 4 to be informative and to increase knowledge about standards, as evident by the answers of “Strongly agree” and “Agree.”

Table 6. Percent of Student Responses to the Module 4 Likert Scale Questions

Question	Likert Scale	Before	After
“In general terms, I am confident that I know what "additive manufacturing" or "3D printing" is.”	Strongly agree	24%	88%
	Agree	40%	12%
	Neutral	26%	0%
	Disagree	10%	0%
	Strongly disagree	0%	0%
“I am confident in my ability to describe the process of 3D printing of concrete and other cement-based materials.”	Strongly agree	22%	84%
	Agree	20%	16%
	Neutral	34%	0%
	Disagree	20%	0%
	Strongly disagree	4%	0%
“I can effectively communicate the limitations of 3D printing of concrete with regard to the need for standardization and/or building design code provisions.”	Strongly agree	22%	84%
	Agree	16%	16%
	Neutral	38%	0%
	Disagree	16%	0%
	Strongly disagree	8%	0%

Table 7. Percent of Student Responses to the Module Effectiveness Likert Scale Questions

Question	Likert Scale	Module 1	Module 2	Module 3	Module 4
“The module provided me with useful information about standards that I did not know before.”	Strongly agree	71%	67%	73%	84%
	Agree	22%	26%	20%	16%
	Neutral	7%	7%	5%	0%
	Disagree	0%	0%	2%	0%
	Strongly disagree	0%	0%	0%	0%
“Overall, I found this module to be helpful in increasing my knowledge of standards related to cements and structural concrete.”	Strongly agree	69%	69%	75%	84%
	Agree	24%	28%	20%	16%
	Neutral	7%	4%	5%	0%
	Disagree	0%	0%	0%	0%
	Strongly disagree	0%	0%	0%	0%

4. Conclusions

The goal of this project was to combine standards education in concrete and cementitious materials with future and emerging technologies to prepare students for sustainability and resilience of the built environment. Four digital modules were developed to focus on (1) Cements and Structural Concrete, (2) High Performance Concrete, (3) Cement and Concrete Sustainability, and (4) Future of Concrete Design and Manufacture. After piloting draft content during two semesters, the revised and final modules were piloted in Spring 2023 to junior and senior undergraduate students. The results of Likert scale questionnaires strongly indicated that the modules were effective and informative. Overall, 93% to 100% of students agreed that the modules provided new and useful information about standards and increase knowledge of standards in the concrete industry.

5. Recommendations

The digital modules proved to be effective in junior and senior undergraduate courses. It is recommended that the content be used in courses related to civil engineering materials, concrete materials, reinforced concrete design, construction technology, and any other course where concrete is discussed.

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