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Workshop Report

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Abstract

The "Additive Construction – The Path to Standardization II" workshop, hosted by the National Institute of Standards and Technology (NIST) and U.S. Army Engineer Research and Development Center (ERDC), brought together key players from the additive construction (AC) industry to tackle the urgent need for standardized guidelines. The discussions focused on the development of standards for materials testing, structural integrity, and safety protocols specific to 3D-printed structures. Central to the workshop discussions was the creation of performance-based standards to ensure reliability and safety in various construction applications, from housing to large-scale infrastructure.

The workshop emphasized the importance of collaboration among industry leaders, researchers, and government bodies to close gaps in current standards and bring domestic codes in line with international ones. Additive construction's potential to reduce material waste, streamline processes, and enhance sustainability was a recurring theme, along with the need for clear, adaptable standards to support innovation without compromising safety. Challenges related to real-world applications and workforce development were also explored.

Through a series of sessions and discussions, participants outlined key obstacles and offered solutions to help advance standardization efforts in the AC field. The workshop participants underscored the importance of continued cooperation, data-driven progress, and developing flexible standards that evolve with advancing technology.

Keywords

3DCP; AC; Additive Construction; Extrusion; Cement; Quality Control; Standards; Testing Methods; Workforce Development.

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1. Executive Summary

The *Additive Construction – The Path to Standardization II* workshop, hosted by the National Institute of Standards and Technology (NIST), brought together industry leaders, researchers, and key stakeholders to address the critical gaps in standards for the growing additive construction (AC) industry. The focus of the workshop was on the development of standards and guidelines for 3D-printed structures, particularly in areas like materials testing, structural performance, safety protocols, and workforce development.

A central theme throughout the workshop was the urgent need of establishing comprehensive, performance-based standards that can evolve alongside rapid advancements in AC technologies. These standards are essential for ensuring the consistency, reliability, and safety of 3D-printed construction across various applications, from residential buildings to large-scale infrastructure projects such as bridge piers or culvert construction.

Participants emphasized the importance of collaboration between industry, academia, and government agencies to fill the current gaps in standards and align international and domestic codes. Additionally, sustainability was highlighted as a key driver for AC, focusing on reducing material waste, optimizing construction processes, and incorporating environmental metrics into standards development.

The workshop sessions and breakout discussions yielded several key findings and recommendations:

Key Findings

This summary highlights the major conclusions drawn from the workshop's discussions and breakout sessions.

Standards Development for Testing and Materials:

> A significant takeaway was the need for standardized, application-specific testing methods to ensure the quality and safety of 3D-printed structures. These methods are necessary for evaluating load-bearing elements, reinforcement systems, and key material properties like rheology and curing behavior. Ensuring consistent sampling procedures and post-print evaluations are critical for quality assurance.

Material and Process Standardization:

> Participants stressed the importance of developing comprehensive material property tables, such as those covering shrinkage and cracking rates for 3D-printed concrete. Linking fresh material properties to their cured performance will help create reliable pre- and post-construction testing frameworks. Addressing material consistency, especially when using locally sourced materials, was seen as crucial for maintaining reliability across different geographic regions.

Safety and Workforce Development:

The shortage of skilled labor in the AC industry was identified as a significant challenge. Workshop participants called for targeted training programs to equip workers with the necessary skills to operate advanced 3D printing technologies. Safety standards for both workers and structures were seen as vital, balancing the need for innovation with robust safety protocols to prevent accidents and structural failures.

International and Domestic Code Alignment:

European countries are ahead of the U.S. in developing AC standards, having prioritized the technology earlier. Participants highlighted the need for greater international collaboration to create unified global standards, which would facilitate the broader adoption of AC technologies. The newly launched Additive Construction by Extrusion (ACE) Consortium aims to address these challenges by fostering collaboration and guiding the development of cohesive standards.

Sustainability Considerations:

Sustainability was identified as a key advantage of additive construction, with its potential to reduce carbon emissions, optimize material use, and minimize construction waste. However, logistical challenges, such as material transportation and site setup, need to be addressed. Participants recommended incorporating sustainability metrics, such as reduced cement usage and the use of locally sourced materials, into future standards.

Challenges of Real-World Application:

The field application of AC technologies faces several practical challenges, including variability in material curing and the complexity of on-site printing. More field data was emphasized to refine existing guidelines and develop new standards tailored to real-world conditions. Bridging the gap between laboratory research and on-site construction will be critical for successfully implementing AC technologies.

Conclusion:

The *Additive Construction – The Path to Standardization II* workshop provided a roadmap for advancing the AC industry by identifying key areas where standards are lacking and proposing solutions to address these gaps. The development of standardized testing methods, material consistency protocols, safety measures, and sustainability practices will be essential for the continued growth of 3D-printed construction. Collaboration between stakeholders and alignment of international and domestic codes are crucial steps toward establishing a robust and adaptable standardization framework that supports innovation while ensuring safety and efficiency in the industry.

2. Introduction

2.1. Workshop Purpose

To convene industry stakeholders to identify and address gaps in current standard documents, focusing on materials, testing methods, and engineering design needs, to advance the standardization and future development of additive construction technologies.

2.2. Workshop Overview

The National Institute of Standards and Technology (NIST) Engineering Laboratory (EL) Materials and Structural Systems Division (MSSD) studies the durability and service life of infrastructure materials (polymer, concrete, engineered composites) for resilience infrastructure applications. One key research focus is the development of Additive Construction (AC) methods, materials, and measurement requirements. Additive construction by extrusion (ACE) has the potential to revolutionize construction by complimenting the existing workforce, eliminating the need to construct formwork, and enabling architectural or structural designs that conventional practices cannot achieve. As ACE has progressed over the past few years, the development of standards has not kept pace, and the need has become essential to promote the industry and ensure safe structures.

NIST has the unique opportunity to aid in the development of the measurement science tools and scientific knowledge base to support the industry's needs of performance-based standards for 3-D printed concrete structures. This objective will be aided by supporting the implementation of all aspects of structural design and related testing standards and engineering guidelines. To do so, a stakeholder's workshop in collaboration with The Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL), was held September 26th and 27th 2023, where discussions focused on the industry needs relative to the structural aspects of additively constructed structures. The workshop also served as a launch event for a new consortium, the Additive Construction by Extrusion (ACE) Consortium, which provides connections between NIST and other stakeholders to continue needed work in this field. As the path continues, a second workshop was held August 20th and 21st, 2024 to review the current state of the industry and develop prospective agendas moving forward.

This workshop, *Additive Construction – The Path to Standardization Continues*, brought together industry stakeholders, academia, and government agencies to discuss gaps in the current standard documents and how the industry can fill these gaps. This workshop included presentations, discussions, and breakout sessions directed towards the current state and desired future state for the additive construction industry, research and development (R&D) needs, timelines, and action items. Topics focused on the materials and testing methods related to additive construction and the needs of the industry with respect to engineering design, standards, and guidelines. Participants in attendance were from industry, government, and research organizations to participate in the workshop along with representation from several ASTM and ACI technical committees. The workshop discussions contributed to the continuing development of a roadmap for standardization of printing and testing methods.

3. Session 1.1: Progress & Lessons Learned

3.1. Additive Construction – The Path to Standardization: Workshop I Recap

NIST hosted the *Additive Construction – The Path to Standardization: Workshop I* on September 26-27, 2023, to explore the essential steps for developing standards and codes in the additive construction (AC) industry. Presented by Shawn L. Platt, Ph.D., the workshop brought together industry leaders to discuss the challenges and opportunities of additive construction, focusing on existing ASTM standards and future guidelines needed to advance the industry.

The workshop was structured into three major sessions:

1. Engineering and Design Needs
2. Standards
3. Guidelines

Key Themes

A recurring theme throughout the workshop was the need for community alignment in the additive construction space. Participants recognized that continued collaboration is essential for the industry to move forward efficiently. There was consensus among the participants that the workshop series should be sustained over the coming years to maintain momentum and ensure progress.

Another major challenge highlighted was reluctance to adopt new technology, a common issue when introducing new methods and materials in the construction sector. To overcome this, participants suggested that workforce unions be involved and that training and educational programs such as the NIST AC Academy be developed to equip workers with the necessary skills.

The workshop also underscored the need for test methods specific to additive construction. To address this gap, participants proposed initiating a program dedicated to investigating application-specific test methods. The initial focus would be evaluating existing standards' efficacy and comparing them to newly proposed methods.

Additionally, structural design guidelines are clearly needed, which led to the launch of efforts by ASTM and ACI. More developments in this area are expected to follow. However, a lack of field data also hinders the refinement of these guidelines. A NIST database, to be initiated through the ACE Consortium, is under construction to address this gap by consolidating relevant data.

The workshop identified several priority areas where standards are needed for the industry to progress:

- **Sampling standards**: Standardized procedures for sample size, rate, orientation, and fabrication are crucial. Standard shapes for test samples, such as cubes or cylinders, also need to be defined.
- **Application-specific test methods**: Structural and process-based test methods are required for specific applications, including load-bearing walls and reinforcement types. These methods should measure key factors such as rheology, viscosity, modulus, and yield.
- **Print resolution standards**: Precision is critical in additive construction, so test methods are needed to assess print accuracy.
- **Standard material tables**: Establishing tables with material property data, such as cracking and shrinkage rates for mortar and concrete, is a foundational requirement for industry consistency.
- **Test methods for cured material**: It is essential to develop methods to test the mechanical properties, layer consistency, and interlayer bonding in cured materials. Participants also emphasized that hardened properties should be linked to fresh property test results and field measurements.

Overall, the workshop laid a clear pathway toward developing codes and standards for additive construction. As the industry evolves, continued collaboration and data collection will be critical in ensuring AC technologies' successful adoption and standardization.

3.2. Additive Construction by Extrusion (ACE) Consortium Update

The Consortium was initiated in April of 2023 and began operations in October of that same year. It was established to bring together stakeholders to identify and address gaps in current standards related to materials, methods, structural performance, and engineering design. The Consortium efforts are intended to study the measurement science needs for the successful adoption of ACE by the construction industry, and to identify and propose new standards to address industry needs not met by existing standards.

Correlating Off-Line Measurements to Print Quality

A focus will be on correlating off-line measurements of fresh and hardening ink to a measure of print quality. The objectives are to determine material performance characteristics critical to ACE's success.

In-Situ and In-Process Measurements

A focus will be on developing in-situ and in-process measurements that may be used to provide feedback into the control of the ACE process. The objective is to implement material property measurements in line to the ACE process.

Hardened Properties and Scaling up From Paste to Concrete

A focus will be on measurements at the structural scale, including proper consideration of in-field issues including, but not limited to, hardened property measurements, studies on curing practices and finishing procedures, and the development of numerical simulations of material deposition. The objectives are to develop measurement techniques to assess hardened properties of 3–D printed structures and investigate how early age properties and measurements may inform ACE through numerical simulations.

Current Task Groups in support of the Consortium's efforts

- Education
  - Objectives: Develop a training program for AC targeted at new users, recent grads, transitioning workforce, and possible interaction with trade organizations.
- Bonding (layer, cold joint, etc.)
  - Objectives: Develop reliable insitu closed loop test methods for bond evaluation. Tasks include round robin testing programs for materials, equipment, and test methodologies.
- Sustainability
  - Objectives: Support public knowledge regarding the sustainability of AC. Develop guidance documents for ACE and the general industry/ public.
- Infrastructure (culverts, pipes, bridges, etc.)
  - Objectives: Investigate infrastructure related opportunities and provide documentation on current interest and needs.
- Durability – Freeze/Thaw
  - Objectives: Develop industry appropriate evaluation methodologies related durability including exposure and testing parameters.
- Test procedures – Field vs. Laboratory
  - Objectives: Corelate testing methods with field applicable requirements.

Key Takeaways

- **Emerging Prescriptive Standards**: The industry anticipates the development of rigid standards to address geometric optimization and the use of validated models to expand the scope of certified system geometries.
- **Unified Standards for On-Site and Off-Site Printing**: The goal is to develop consistent standards that apply equally to the 3D printing of structural concrete elements on-site and off-site.
- **Importance of Coordination**: Effective coordination among key organizations like ICC, ACI, ASTM, and NIST is crucial to ensure consistency, identify and fill gaps, and reduce duplication in efforts across the industry.

- **Ongoing Development of Structural Design Standards**: Structural design and building standardization efforts are still in progress, with reports and guidelines expected to be completed within the next year.
- **Exhibiting Successful Use of New Technology**: Ongoing efforts to construct small-scale structures can serve as exhibits demonstrating the positive results of new 3D printing technology.
- **Challenges in Government Adoption of Additive Construction**: While additive construction (AC) has potential benefits, including aligning with modernization goals like reducing CO_2 emissions, it must be cost-competitive to gain wider adoption. Government investigations are ongoing, but no specific proposals have been made (as of the date of this workshop).
- **Lack of Finalized Testing Methods**: The industry is still investigating various testing methods for additive construction, and no finalized or widely accepted standards have yet been established.

The consortium, Additive Construction by Extrusion (ACE) Consortium, is active on the Federal Register:

https://www.federalregister.gov/documents/2023/09/12/2023-19647/additive-construction-by-extrusion-ace-consortium.

3.3. American Society for Testing and Materials (ASTM) Update

Stephan Mansour, Associate Consultant, ASTM International, Wohlers Associates, provided an update on the list of active standards and those currently under development within ASTM F 42.0 7.07. They are as follows:

WK74302 - (Specification) Additive Manufacturing for construction – Process characteristics and performance – Specification for manufactured polymeric UV cured structures for residential applications.

WK78110 - (Guide) Additive Manufacturing – General Principles – Development and Road mapping of Additive Construction Standards

WK81114 / ISO/ASTM 52962 - (Guide) Standard Additive Manufacturing – General Principles – Design Process of Additively Manufactured Building Components

WK84415 / ISO/ASTM 52963 - New Practice for Additive Construction – General Principles – Evaluation of Structural Printed Elements

WK89299 - (Specification) Additive Manufacturing for construction – Qualification principles – Structural and infrastructure elements. Revision of ISO/ASTM 52939 published in December 2023

WK89706 - Standard Practice for Additive Manufacturing -- Fresh and Very Early Age properties of concretes used for Additively Constructed Concrete by Means of Extrusion

WK89707 - Standard Practice for Additive Manufacturing -- Construction and Documentation of Additively Constructed Concrete and Mortar Components

WK90347– Standard Practice Additive Manufacturing -- Curing and Extraction of Sample from Additively Constructed Concrete and Mortar Components

WK90348 - Standard Test Method Additive Manufacturing -- Determination of Hardened Mechanical Properties of Additively Constructed Concrete and Mortar

4. Session 1.2: State of the Industry and Challenges it Faces

The presentation titled *State of the 3DCP Industry and Challenges it Faces* delivered by Bing Tian, Ph.D., included contributions from Abdul Peerzada, Ph.D., and Austin Sanderson from The Quikrete Companies, outlined the current status of the 3D Concrete Printing (3DCP) industry, its challenges, and potential future directions. The key points shared in the presentation and insights from the subsequent Q&A session are summarized below.

3DCP Industry Progress

The presentation highlighted the success of 3DCP in residential housing, attracting public interest and investments from entrepreneurs and startups. Despite these advancements, the industry still faces several critical challenges limiting broader adoption. Only a few hundred 3D-printed houses have been completed worldwide, with notable projects such as ICON's Wolf Ranch in Georgetown, Texas, and architectural installations at the Coachella Festival demonstrating the potential of 3DCP technology.

Challenges Facing the 3DCP Industry

A survey conducted by Smartbrief.com revealed the primary challenges faced by the industry, including the lack of codes and standards, concerns about structural performance, issues with printability and buildability, reinforcement, and cracking. The presenter expanded on these challenges with their observations:

- **Pre-packaged 3DCP Mix:** While offering better control and consistency, pre-packaged 3DCP mixes are still costly due to limited production and the made-to-order nature of the market. On the other hand, field mixes pose quality control challenges, particularly with variations in raw materials and ambient conditions. The presenter expressed optimism that pre-packaged mix costs could decrease as the industry scales up and production volumes increase.
- **Fluctuating Ambient Conditions:** Environmental factors, such as temperature, humidity, and wind, present significant challenges for on-site 3D printing. The presenter noted that measuring the water-to-cement (w/c) ratio alone is insufficient for monitoring the material quality, especially when long hose segments and extreme temperatures are involved. While viscosity sensors are still in development, the interim solution is to use flow testing on-site. Integrating temperature sensors and water-controlling systems, such as chillers, into 3D printing systems is essential to maintaining consistent print quality and reducing cracking.
- **Technical Infrastructure:** The need for monitoring and adjustment systems on-site is a significant hurdle for 3DCP. The ready-mix concrete industry, which uses in-transit monitoring systems like the Verifi+ Admix system, was presented as a model for how the 3DCP industry can improve quality control and consistency.

Future Challenges

Several future challenges for the 3DCP industry were identified, with insights from both the presentation and the Q&A session:

- **Transition from Mortar to Concrete:** Currently, most 3DCP projects use mortar, but future developments are expected to shift toward 3DCP concrete. Concrete, which uses larger aggregate sizes, offers greater structural integrity, reduced cracking, improved durability, and better cost-efficiency than mortar. However, this transition will require advancements in printing machinery capable of handling larger aggregates.

- **Two-Component (2K) Systems:** The next generation of 3D printing systems is expected to involve two-component (2K) systems, which allow for on-site adjustments of admixtures to accommodate changes in weather conditions and aggregate moisture. The flexibility of the 2K system makes it advantageous for real-time adjustments, but continuous mixing systems, where admixtures are injected at the printing head, face challenges in terms of precise dosing and mixing in a small chamber. Batch mixing is preferred due to its reliability in maintaining the proper admixture balance.
- **Comparison with Traditional Construction Methods:** The presenter highlighted that 3DCP must compete with established methods like CMU (Concrete Masonry Units) walls, which have a lower carbon footprint and are currently more cost-efficient. While CMU walls remain a viable option, 3DCP offers significant advantages in terms of customization, particularly for complex structures, contours, and shapes that CMU cannot easily achieve.
- **Prefabrication vs. On-Site Printing:** The presenter strongly supported prefabrication as a strategic step for advancing the 3DCP industry, especially when dealing with reinforcement and complex shapes. Pre-fabricating components in controlled environments can reduce the impact of fluctuating environmental conditions and improve overall quality control.
- **Alternative Binder Systems:** Alkali-Activated Systems (AAS) and Geopolymer systems were discussed as alternatives to Ordinary Portland Cement (OPC). These alternatives are more expensive and present challenges related to supply and environmental impact. Further research and development are needed before they can be widely adopted.

Key Industry Needs

The presenter emphasized the critical need for standardization across the 3DCP industry. Standards are required for the following areas:

- **Sampling standards** to address sample size, rate, and orientation.
- **Application-specific test methods** for critical components like load-bearing walls and reinforcement types.
- **Print resolution standards** to ensure accuracy and consistency in printed structures.
- **Material standards** to ensure durability and consistency, with an emphasis on both fresh and hardened properties.

Summary and Conclusions

In conclusion, while 3DCP is an innovative technology with great potential, it remains in its infancy. The industry must overcome significant challenges in standardization, structural performance, and environmental adaptability. Greater investment and collaboration are necessary to address these issues, and the technology needs to mature further before it can be widely adopted. The presenter cautioned against misconceptions and unrealistic expectations as construction applications advance faster than the underlying research and technological capabilities.

The presentation concluded by emphasizing the importance of continued research, development, and collaboration among industry stakeholders to ensure the successful adoption and growth of 3DCP technologies.

Session Q&A Transcript

The transcript of the Q&A session can be found in the Appendix: Appendix D: State Of The Industry And Challenges It Faces Q&A

5. Session 1.3: Printing Formats and Challenges to Standardization

The presentation *Printing Formats and Challenges to Standardization* was delivered by Eric L. Kreiger, PE, Researcher at the U.S. Army Engineer Research and Development Center (ERDC)and Chair of ASTM 564-OB . The session aimed to broaden the perspectives of participants regarding the deployment of additive construction (AC) technologies and to encourage a rethinking of how to approach the standardization process. Kreiger emphasized that the successful deployment of these systems—especially in challenging environments such as military deployments and Humanitarian Aid/Disaster Response (HADR) missions—depends on using equipment that can operate independently without relying on complex systems that may fail in the field.

Key Takeaways

- **Diverse Printer Formats**: The presentation highlighted various types of printer formats used in AC, including robotic arm systems, gantry systems, and other configurations. These printers can be deployed in different settings, such as stationary commercial applications, mobile commercial systems, and deployable systems suited for military use or disaster relief efforts. The key takeaway is that the printer format must be selected based on the application, especially in mission-critical environments where a single equipment failure could jeopardize an entire operation.
- **Material Agnosticism**: Kreiger suggested that printers should be considered "material agnostic," meaning the focus should be on the materials delivery system rather than the printer itself. The performance of AC technology hinges more on how materials are delivered consistently and reliably, rather than the specific type of printer being used. This perspective shifts the focus of standardization efforts toward optimizing material handling and delivery systems.
- **Understanding Structural Design in AC**: While AC technologies are proving capable of meeting structural requirements, Kreiger pointed out that the AC community still lacks a comprehensive understanding of how to best design these structures. Design methodologies are evolving through testing and validation, with both simple material tests and more refined sensor-based evaluations being explored to determine structural acceptance criteria.
- **Cast vs. Printed Materials**: A major point of discussion was the difference in material behavior between cast materials and those printed using AC. This distinction needs to be better understood to develop appropriate design criteria and ensure structural integrity. Acceptance tests and methods for AC need to reflect the unique challenges posed by these differences.
- **Operational and Environmental Challenges**: Kreiger underscored the operational challenges associated with AC in the field, particularly the limitations of the material delivery system, time constraints, and environmental conditions such as weather. These factors must be accounted for when developing standards, especially in remote or high-stakes deployment scenarios.

Session Q&A Transcript

The transcript of the Q&A session can be found in the Appendix: Appendix E: Printing Formats and Challenges to Standardization Q&A

6. Breakout Session 1: Hurdles to Field Printing

During Breakout Session 1.1, participants explored the challenges and hurdles associated with translating 3D printing technology from lab-based settings to field applications. The session focused on identifying key obstacles that impact the effectiveness and consistency of 3D printing in construction environments, with particular attention to the differences between controlled laboratory conditions and real-world job sites. Categories such as rheology, curing, testing, and printing procedures were examined, with participants contributing their insights on the hurdles that limit scalability and efficiency in field printing.

Participants brainstormed potential solutions to some of these challenges, providing recommendations to improve processes and mitigate risks in key areas. The report highlights hurdles such as inconsistencies in material flow, the need for real-time monitoring methods, challenges in curing due to environmental variability, and the absence of standardized testing methods. Each challenge was rated by participants in terms of 1.) whether they experienced the hurdle, and 2.) its impact level (high, medium, low), and while time constraints prevented all hurdles from being addressed with solutions, several actionable recommendations were proposed, including advancements in material testing, automation, and the need for industry-wide collaboration.

This section provides a comprehensive summary of the identified hurdles and potential solutions, offering valuable insights into the urgent steps required to bridge the gap between lab and field applications in 3D printing for construction. The potential impact of these hurdles on the industry is significant, and it is crucial that we address them promptly.

6.1. Rheology Hurdles & Potential Solutions/Recommendations

The **rheology hurdles** gathered by the participants identify key challenges that affect the flow and deformation behavior of materials, particularly in 3D concrete printing and other construction processes that rely on precise material performance.

A summary of these hurdles and potential solutions is presented below, listed in order by size (number of votes) and severity [high, medium, low] as rated by the participants. Note: Due to limited time, participants could only brainstorm some solutions.

Hurdles & Potential Solutions/Recommendations
• **Lack of In-Situ Monitoring Method**: The absence of effective in-situ monitoring methods during 3D printing makes it difficult to control rheological properties in real time, leading to potential inconsistencies in the final structure. (9) [High] *Potential Solution(s)/Recommendations:*

- Ongoing financial investment in hardware and sensor development specific to construction-scale 3D printing.

- **Tearing and Cracking**: Inadequate control of rheology can result in defects such as tearing or cracking during or after printing, especially as the material sets and dries. These defects reduce the structural strength of the final product. (3) [High]
- **Interlayer Bond**: Achieving strong bonding between printed layers is critical for structural integrity. Poor bonding can lead to weak points in the structure, compromising its durability and load-bearing capacity. (3) [High]
- **Suitable Rheology Across the Open Time**: The "open time" refers to the period during which the material remains workable. Maintaining suitable flow properties during this time is crucial to prevent premature setting or hardening before the printing process is completed. (2) [High]
- **Correlation of Rheological Properties to Printed Performance**: Establishing a clear relationship between material flow (rheology) and the final quality of the printed structure is challenging. Understanding how rheological properties impact performance is essential for optimizing the printing process. (0) [High]

  Potential Solution(s)/Recommendations:
  - Active rheology control - currently operator controlled (reactive, qualitative); proactive (quantitatively) - data collection and correlation from rheology tests before through print performance and followed by curing. Future automated solutions.
  - Machine learning.

- **Consistency of Materials**: Ensuring consistent material properties throughout the printing process is challenging. Variations in material consistency can lead to uneven layer deposition and affect structural integrity. (6) [Medium]

  Potential Solution(s)/Recommendations:
  - Continuing trial batches and ongoing material and mixture design development, on-site testing, prequalification to capture system/material variability.

- **Measurement**: Accurately measuring rheological properties, such as viscosity and yield stress, is difficult. Without reliable data, it becomes challenging to adjust material flow and consistency during the printing process. (2) [Medium]
- **Inconsistent Workability**: The workability of the material can vary throughout the printing process, making it difficult to maintain smooth layer deposition and uniform structural properties. (2) [Medium]

  Potential Solution(s)/Recommendations:

  - Continuing trial batches and ongoing material and mixture design development, on-site testing, prequalification to capture system/material variability.

- **Rheology After Addition of Accelerator**: Adding accelerators to concrete mixes can alter rheological properties, speeding up the curing process but potentially leading to issues with material flow and layer bonding. (1) [Medium]

  Potential Solution(s)/Recommendations:
  - Ongoing hardware development and investments; create new ASTMs for specialty aggregate sources that are not strictly for CMU and Concrete.

- **Relationship Between Mixer and Printer Nozzle Varies with Temperature/Time of Day**: Temperature fluctuations throughout the day can affect the interaction between the material, mixer, and printer nozzle, leading to inconsistencies in material flow and print quality. (1) [Medium]
- **Change in Rheology as Concrete Ages**: As concrete sets and cures, its rheological properties evolve, making it harder to ensure proper bonding between new and previously set layers. This change in properties complicates the printing process. (0) [Medium]
- **Test Results Don't Match from System to System**: Test results for rheological properties often vary between different printing systems, making it difficult to standardize and predict material performance across various machines and processes. (4) [Low]

  Potential Solution(s)/Recommendations:
  - Prequalification of individual systems (combo of material batching and delivery system, printer, and material) before projects so guessing and extrapolation is eliminated.

- **Aggregate Size in Relation to Rheological Properties for Printing or QC Measurements**: The size of aggregates in the concrete mix has a significant impact on rheology. Larger aggregates make it more difficult to achieve smooth material flow, while smaller aggregates may reduce the material's structural strength. (4) [Low]
- **Reliance on Empirical Method**: Current rheological testing and control methods rely heavily on empirical data, which may not always provide accurate predictions of material behavior, leading to inconsistencies in the printing process. (2) [Low]
- **Changes in Raw Material Fineness/More Water Demand**: Variations in the fineness of raw materials can impact the water demand of the mix, affecting its flowability. Higher water demand can reduce the strength of the material and increase the risk of deformation during printing. (1) [Low]

- **Inability to Use Coarse Aggregate**: Coarse aggregates, which are commonly used in traditional construction, often cannot be used in 3D printing due to their impact on material flow, limiting the strength and versatility of printed structures. (1) [Low]
- **Lab Simulation of Pumping Effects on Fresh Mortar Without Full-Size Equipment**: Simulating how fresh mortar behaves in laboratory settings, without using full-scale equipment, can lead to inaccurate results, making it difficult to predict real-world performance. (0) [Low]
- **Getting Data from Highly Thixotropic 1k Mixes**: Highly thixotropic 1k mixes, which exhibit complex flow behaviors, are difficult to measure and control. Gathering accurate data on their properties is a challenge, complicating the optimization of printing parameters. (0) [Low]
- **Water Consistency**: Maintaining consistent water content throughout the printing process is essential for controlling rheology. Variations in water content can lead to inconsistent flow, affecting the quality of the printed structure. (0) [Low]

Potential Solutions/Recommendations Not Linked to a Hurdle:

- Optimize Aggregate Size vs Nozzle Size.
- Humidity control.
- Admixtures.
- Temperature control.

6.2. Curing Hurdles & Potential Solutions/Recommendations

The list of **curing-related hurdles** highlights the complexities of managing moisture, temperature, and environmental factors during the curing process in 3D printing.

A summary of these hurdles and potential solutions is provided below, listed in order by size (high, medium, low) as rated by the participants. Note: Due to limited time, participants could only brainstorm some solutions.

Hurdles & Potential Solutions/Recommendations

- **Shrinkage**: As the material cures, it tends to shrink, which can lead to cracking or deformation in the structure. Controlling shrinkage during the curing process is essential to maintain the integrity and shape of the printed structure. (4) [High]
- **Lack of Standards**: There is a lack of standardized guidelines for curing 3D-printed materials, leading to variability in how different companies or

projects approach curing. This lack of standards complicates quality control. (3) [High]

- **Environmental Variability**: External factors such as temperature, humidity, and weather conditions can vary significantly during the curing process, leading to inconsistencies in how the material cures and potentially weakening the structure. (5) [High]

  Potential Solution(s)/Recommendations:

  - In-line monitoring, QA/QC.
  - Make sure samples collected represent the full range of environmental conditions for the print job.

- **Size of Specimens**: Larger printed specimens require different curing approaches compared to smaller samples. Controlling the curing process for larger structures is more complex and often harder to manage, leading to variability in performance. (4) [High]

  Potential Solution(s)/Recommendations:

  - Sample tests should conform to the actual print widths/thicknesses and acknowledge aggregate size.
  - Develop standards.

- **Rapid Evaporation**: Fast evaporation of water during curing, especially in hot or windy environments, can cause uneven drying, leading to surface defects and internal cracking. (2) [Medium]
- **Crack Formation**: Cracks can form during the curing process due to factors like shrinkage, rapid drying, or improper curing techniques. These cracks weaken the material's structural integrity and durability. (2) [Medium]
- **Wet Curing Versus Curing Compounds**: Choosing between wet curing (keeping the material moist) and curing compounds (which create a protective layer to retain moisture) impacts the final strength and quality. Each method has trade-offs that affect performance during curing. (2) [Medium]
- **Moist Curing or Curing Compounds (Effect on Interlayer Bonding)**: Choosing between moist curing and curing compounds can have a direct effect on the bonding between layers, especially if curing compounds interfere with the bonding after a printing break. (3) [Medium]
- **Early-Age Protection Negatively Affecting Bead Quality**: Protection methods applied during the early stages of curing can sometimes degrade the quality of printed beads (layers), impacting the surface texture and structural properties of the final product. (3) [Medium]
- **Continuous Operations vs. Discrete Placements**: The decision between continuous printing operations and discrete placements during curing can

affect how consistently the material sets. Discrete placements may lead to inconsistent bonding and curing across different sections. (3) [Medium]

- **Changing Ambient Conditions Between Prints**: Variations in temperature, humidity, or wind between printing sessions can result in inconsistent curing, causing poor bonding between layers and potential structural defects. (1) [Medium]
- **Manpower Associated with Moist Curing**: Effective moist curing requires skilled labor to apply moisture evenly. Without the right manpower, the curing process may become inconsistent, weakening the structure. (2) [Low]
- **Plastic Tarp vs. Fresh Material**: Using plastic tarps to cover fresh material during curing can help retain moisture, but improper application may result in uneven moisture retention and inconsistent curing. (2) [Low]
- **Product vs Wrap**: Deciding whether to cover the material with plastic wrap or leave it exposed influences the curing process. Proper use of a wrap can help retain moisture, but if not applied correctly, can lead to inconsistent curing or other issues. (1) [Low]
- **Humidity Control for Hydration**: Proper hydration is crucial during curing, and controlling humidity levels ensures the material sets correctly. Inconsistent humidity can lead to improper curing, reducing strength and durability. (3) [Low]
- **How to Get the Proper Mix Properties**: The composition of the material mix plays a crucial role in the curing process. Finding the optimal balance of ingredients is key to ensuring the material cures evenly while maintaining its desired strength and durability. (0) [Low]

Potential Solutions/Recommendations Not Linked to a Hurdle:

- Chemistry of the material itself.
- Keep the wall being printed damp.
- Evaporation retarder.

6.3. Testing Hurdles & Potential Solutions/Recommendations

These **testing-related hurdles** highlight the challenges in accurately evaluating the quality and performance of 3D-printed structures. Here's a summary of these hurdles and potential solutions listed in order by size (high, medium, low) as rated by the participants. Note: Due to limited time, participants could only brainstorm some solutions.

Hurdles & Potential Solutions/Recommendations

- **Lack of Testing Standards**: The lack of widely accepted standards for testing 3D-printed structures creates inconsistency in quality and safety assurance. (7) [High]

  Potential Solution(s)/Recommendations:

  - Testing, reviewing, and revising the test methodology. Continuous, multiple parties, backed by data collection and statistical analysis.
  - Ongoing committee work.

- **Standards**: The lack of widely accepted standards for testing 3D-printed structures creates inconsistency in quality and safety assurance. (5) [High]

  Potential Solution(s)/Recommendations:

  - The path to standard requirements requires comparable interlaboratory data generation. NIST AC lab is working on some initial methods/fixtures to share with academia and industry that could support this hurdle.

- **How to Make Representative Samples**: Creating test samples that accurately reflect the properties of the final printed structure is a challenge. (6) [High]

  Potential Solution(s)/Recommendations:

  - Situational and application specific - don't know what the tests will be yet - still in the "borrowed" stage, that is the tests currently follow methods for other materials not related to printability.
  - Using a scaling factor with a cast specimen is not necessarily representative of in-situ printed quality. Field cured; field printed samples are most representative but difficult to fabricate/extract. A strategy to minimize sampling requirements, but still focus on in-situ printed specimens, would be most appropriate. That strategy could include using cast specimen and lab specimen statistics and checking that the in-situ printed samples are within certain thresholds. (Add in fibers that self-orient during printing, and cast specimens become even less reliable.)
  - Develop a validated Finite Element Analysis (FEA) model whose results are shown (through testing) to be insensitive to a range of geometries.
  - Standards development.

- **Cast vs. Printed Specimens**: There are significant differences between cast (traditional) and 3D-printed concrete specimens, especially in terms of layer bonding and material behavior. (4) [High]

  Potential Solution(s)/Recommendations:

  - Using a scaling factor with a cast specimen is not necessarily representative of in-situ printed quality. Field cured; field printed samples are most representative but difficult to fabricate/extract. A strategy to minimize sampling requirements, but still focus on in-situ printed specimens, would be most appropriate. That strategy could include using cast specimen and lab specimen statistics and checking that the in-situ printed samples are within certain thresholds. (Add in fibers that self-orient during printing, and cast specimens become even less reliable.)

- **Variable Print Geometries**: Testing structures with varying geometries complicates the testing process, as different geometries behave differently under stress, making it harder to create standardized testing methods. (9) [Medium]
- **Range of Applicability (Environmental and Material Tolerances)**: Testing must account for a wide range of environmental and material tolerances (e.g., humidity, temperature, material consistency) to ensure that the results are reliable across different conditions. (2) [Medium]

  <u>Potential Solution(s)/Recommendations:</u>

  - Test at extreme ends of range, test worst case, record conditions and gather dataset for generating conclusions, develop allowable tolerances.

- **Building Code Expectations**: Ensuring that 3D-printed structures meet existing building codes is often unclear. (4) [Medium]
- **How to Evaluate Bond Strength?**: Evaluating the bond strength between printed layers is critical to ensure that the structure is durable. (4) [Medium]

  <u>Potential Solution(s)/Recommendations:</u>

  - Design considerations for where a cold joint effect will be minimized.
  - Understand material/printing conditions necessary to get interlayer bonding and incorporate maximum layer print time as part of the standard.
  - C1583 modified, discussed in ICC; for repair: epoxy injection, methyl methacrylate injection, CFRP, etc.

- **Testing Method**: Determining appropriate methods for evaluating 3D-printed structures is difficult. (3) [Medium]
- **Lab vs. Field Testing**: A gap exists between laboratory conditions and real-world performance. Lab tests may not accurately simulate the environmental stresses or conditions experienced on-site, which can lead to discrepancies between test results and actual performance. (3) [Medium]
- **Lab vs. In-Suite Testing**: A gap exists between laboratory conditions and real-world performance. (3) [Medium]

- **Scaling Up Test Results to Larger Systems**: Scaling test results from small-scale models to full-scale structures is not straightforward. (3) [Medium]

  Potential Solution(s)/Recommendations:

  - Sequenced testing covering a range of applications such that analytical modeling can be predictive of scalability.

- **Variable Bead Geometries**: The geometry of printed beads (layers) can vary, complicating the testing of printed structures. (4) [Low]
- **Burden of Making Small Testing Walls Paired with Printed Structures**: Creating small-scale test walls that accurately represent larger printed structures is time-consuming and resource-intensive. (4) [Low]
- **Lab Simulation of Real Field Exposure Conditions**: Simulating real-world conditions such as temperature, humidity, and curing in a lab is difficult. (4) [Low]
- **Inconsistent Sample Postprocessing**: The way samples are processed after being printed (e.g., curing) can vary and lead to inconsistent results. (5) [Low]
- **Cold Joint Treating and Its Validity**: Cold joints between printed layers present challenges for ensuring structural integrity. (5) [Low]

  Potential Solution(s)/Recommendations:

  - Need boundaries to operate within. Qualification stage, not throughout a print.
  - Prequalify system including cold joint treatment procedure.
  - Distinguish reinforced/unreinforced applications. For cold joints, assume that one has to design for compression only with zero tensile strength.
  - Testing and standards development.

- **Lack of Research Data**: There is insufficient data on the long-term performance of 3D-printed structures. (4) [Low]
- **Lack of Testing Equipment Designed for Field Deployment**: Most testing equipment is designed for use in controlled lab environments. (2) [Low]
- **Lack of Nationwide Building Codes**: The absence of unified national building codes for 3D-printed structures creates challenges for ensuring compliance across different regions. (1) [Low]
- **Transportation of Large Samples**: Transporting large printed samples to testing facilities. (1) [Low]
- **Density of Mix; Speed of Mix Control and Sensors on Equipment**: The density of the mix and speed at which it is applied during printing can vary. (0) [Low]

- **Timing (Before, During, and After Printing)**: Knowing the right time to conduct tests (whether before, during, or after printing).(0) [Low]
- **Who Should Be Responsible for What Documentation?**: Confusion often arises over who is responsible for documenting test results and ensuring compliance with safety standards. (0) [Low]

Potential Solutions/Recommendation Not Linked to a Hurdle:

- Proper water temperature and regulation.
- The correct hose length.
- Element testing.
- What equipment is best for the jobsite?

6.4. Printing Hurdles & Potential Solutions/Recommendations

These **printing-related hurdles** highlight the complexities involved in maintaining consistency and quality during the 3D printing process. Here's a summary of these hurdles and potential solutions listed in order by size (high, medium, low) as rated by the participants. Note: Due to limited time, participants could only brainstorm some solutions.

Hurdles & Potential Solutions/Recommendations

- **Changes in Mixture Design Needs Extensive Testing**: Modifications to the material mix require extensive testing. (0) [High]
- **Proper Field Monitoring Systems (Industrial)**: Reliable monitoring systems are essential for tracking the quality of the print. (3) [High]
- **Remote Locations**: Printing in remote areas presents logistical and technical challenges. (0) [High]
- **Splicing of Vertical Reinforcement and Subsequent Inspection**: Incorporating vertical reinforcement, such as rebar, into printed structures is challenging. (0) [High]
- **Variable Time Between Layers**: Variability in the time taken between printing layers. (3) [High]
- **Weather and Environmental Variability**: Environmental factors can significantly affect print quality, including temperature, humidity, and wind. (3) [High]
- **Lack of Trained Workforce**: A shortage of skilled workers trained in 3D printing technology. (3) [High]
- **Balance Between Printability and Cured Properties**: Finding the right balance between how well the material prints and its final cured properties. (0) [High]

- **Printing Speed and Material Rheology Relationship**: The balance between printing speed and material flow properties. (3) [Medium]
- **Remote Locations**: Printing in remote areas presents challenges. (0) [Medium]
- **Waste Material at Start and End of Print**: Significant waste can accumulate at the start and end of the printing process. (4) [Medium]

  Potential Solution(s)/Recommendations:

  - Identify local options for concrete recycling. Minimize ratio of waste to usable material by maximizing up time. Use a coating material on equipment and hoses to ease clean up.
  - Increase proficiency of operators to ensure consistent materials. Control flow so that materials do not continue to flow. Parallel effort to utilize waste material.
- **Clogs Printing with Larger Aggregates**: Larger aggregates in the material mix can cause clogging in the nozzle. (2) [Medium]
- **Repositioning**: Moving or repositioning the printer or material during the printing process. (1) [Medium]
- **Controlling w/c Ratio (Water/Cement)**: Properly managing the water-to-cement ratio. (4) [Medium]

  Potential Solution(s)/Recommendations:

  - Use calibrated flow meters to control water addition, consistency is key. 0.1% matters.
  - Training operator to learn how to control the variable.
- **Layer Bonding of the Materials**: Achieving strong adhesion between layers. (1) [Medium]
- **Experience of Printing Crew**: The skill and experience of the printing crew play a crucial role. (2) [Medium]
- **Temperature Effect on Printability**: Variations in temperature can significantly affect the printability of materials. (1) [Medium]
- **Flatness of the Build Plate/Floor**: The surface on which the structure is printed. (1) [Medium]
- **Equipment Variability**: Differences in equipment can lead to variations in print quality. (2) [Medium]
- **Lack of Consistency in Material Throughout the Day**: Material properties may change throughout the day. (1) [Medium]
- **Uniform Layer (Width/Height) and Good Surface Textures**: Maintaining consistent layer width and height. (3) [Medium]

  Potential Solution(s)/Recommendations:

    - Inline QA/QC measurement with feedback to the printer. Video monitoring at print head for dimensions and surface texture.
- **Clean Out Schedule (+4 hours)**: Regularly cleaning out equipment, particularly after four hours of use. (2) [Low]
- **Nozzle Selection and Geometry of Ribbons**: The shape and size of the nozzle affect the geometry of the material. (0) [Low]
- **Need for Continuous Print Paths**: Interruptions in the print path can lead to defects in the structure. (1) [Low]
- **Bead Height Compensation with Respect to Lower Layer Deformation**: As new layers are printed; the weight and pressure of the material can deform the lower layers. (0) [Low]
- **Flat Surface**: Achieving a flat surface during printing. (0) [Low]
- **Setting Up and Repositioning Larger Printers**: Moving and setting up large 3D printers is a logistical challenge. (1) [Low]
- **Hose Clogs**: Hoses that transport the material to the printer nozzle can become clogged. (0) [Low]

  Potential Solution(s)/Recommendations:

    - Ensure the hose is clean before using (camera scope if needed). Use a coating to run smooth, clean out with sponge balls.
- **Accessibility of Extruding System**: Ensuring the extruding system can access all parts of the structure being printed. (0) [Low]
- **Environmental Conditions**: The environment in which printing takes place—whether indoor or outdoor—can impact the material's curing time, consistency, and overall quality. (0) [Low]

  Slumping on Lower Layers from Weight of Upper Layers: As new layers are added, the weight of the material can cause lower layers to slump or deform. (0) [Low]

6.5. Other Hurdles & Potential Solutions/Recommendations

These **other related hurdles** highlight important operational, logistical, and safety concerns in the 3D printing of buildings. Here's a summary of these hurdles and potential solutions listed in order by size (high, medium, low) as rated by the participants. Note: Due to limited time, participants could only brainstorm some solutions.

Hurdles & Potential Solutions/Recommendations

- **Differing Viewpoints on Importance of Anisotropy and Bond Strength**: Opinions differ on the significance of anisotropy (directional strength differences) and bond strength between printed layers. (7) [High]

  Potential Solution(s)/Recommendations:

  - Standardize code language for design methods and consider specific limit state and load path to determine the significance of anisotropy and bond strength.
  - Represent interlayer forces through FEA model resolution.

- **Regulatory and Building Code Compliance**: Ensuring 3D-printed structures meet regulatory and building code requirements is a challenge. (5) [High]

  Potential Solution(s)/Recommendations:

  - Balance the evolution of standards written for code options with the need for stability and consistency in code language across jurisdictions.

- **Varying Rigors from AHJs (Authorities Having Jurisdiction)**: Different authorities may enforce varying levels of rigor when approving 3D-printed structures. (4) [High]

  Potential Solution(s)/Recommendations:

  - Education is needed at the operational, inspection, design, and code enforcement levels.

- **Workforce Education**: Educating workers on the principles of 3D printing, material properties, and equipment. (3) [Medium]

  Potential Solution(s)/Recommendations:

  - Workforces already familiar with cementitious materials may have the most aptitude for cross-training. Workforces familiar with construction are potentials for cross-training. Other backgrounds may be promising based on their heightened interest in the field, but not necessarily their existing skill set.
  - Develop fall back options.
  - Develop safety programs.
  - Simplify interfaces (GUI).
  - Cross-training of printing teams and associated trades.

- **Water Usage**: Managing water usage during the printing process is crucial for maintaining material consistency. (3) [Medium]

  Potential Solution(s)/Recommendations:

- Develop water recycling systems, study reuse of cleanout water, borrow the same practices from current ready-mix and on-site washout.

- **Equipment Mobility and Setup**: Transporting and setting up 3D printing equipment, particularly in remote or difficult-to-access locations. (3) [Medium]
- **Maintenance of Equipment**: Regular maintenance of 3D printing equipment. (2) [Medium]

  Potential Solution(s)/Recommendations:

  - Consider common testing/certification.
  - Know your machine.
  - Use a pump primer, lubricate hose, training.
  - Virtual Reality (VR) Training.
- **Resulted in More Waste Materials**: The 3D printing process can generate significant waste materials. (2) [Medium]
- **Proper Operator Training**: Skilled operators are essential to manage equipment, control material flow, and troubleshoot problems. (1) [Low]
- **Material Storage**: Proper storage of materials, such as concrete mixes and additives. (1) [Low]

  Potential Solution(s)/Recommendations:

  - Keep them cool.
  - Data logging - temperature and humidity.
  - Be consistent on the material properties and storage.
- **Power Supply and Reliability**: Reliable power is essential for 3D printing operations. (1) [Low]
- **Site Preparation and Ground Stability**: Preparing a stable, level site is critical for successful 3D printing. (1) [Low]

  Potential Solution(s)/Recommendations:

  - Ground stability is key, set up on well-drained, level, and compacted gravel/Dense Graded Aggregate (DGA) at least 6 inches.
- **Assembly of 3D Printed Segments**: In large-scale projects, printed segments often need to be assembled on-site. (0) [Low]
- **Differentiating Printing Flaws from Defects That Compromise Strength or Durability**: Not all visual imperfections in a 3D print affect structural strength. (0) [Low]
- **Stressing the Importance of Safety** Safety is a top priority in 3D printing, just as in traditional construction. (0) [Low]

- **Pump Manufacturers in the US**: A limited number of manufacturers that produce pumps specifically for 3D printing construction. (0) [Low]
- **Correlation of Compressive Strength to Actual Performance**: Understanding how compressive strength, as measured in lab tests, correlates to real-world performance. (0) [Low]
- **Prepackaged Materials Options [Strength and Set Time Grades of Mortar/Concrete Commercially Available]**: The market lacks a wide variety of prepackaged materials optimized for 3D printing. (0) [Low]
- **<u>Potential Solutions/Recommendations Not Linked to a Hurdle:</u>**
- Printer mobility - set up time.
- Labor force training at union and non-union facilities / Workforce training.
- Acceptance by local building codes.

7. Session 1.4: Sustainability

The presentation, *Reducing Carbon Emissions - A Case Study in a 3DP Home*, delivered by Sean Monkman, Vice President - Materials Science at ICON, highlighted a collaboration between ICON and MIT on a lifecycle analysis comparing a 3D-printed (3DP) home to a traditional stick-framed (STF) home. The study examined embodied and operational carbon over a 75-year service life across seven U.S. climate zones. The 3DP home showed equivalent or slightly lower embodied carbon than the STF home. It outperformed STF in annual operational carbon savings, ranging from 2% in mixed-humid climates to 9% in dry-hot climates. Total carbon savings for 3DP homes ranged from 2% in Baltimore to 6% in Phoenix compared to STF homes.

Lifecycle Carbon Emissions:

- Monkman emphasized that 3DP homes offer lower operational carbon emissions than STF homes across various U.S. climate zones, with annual savings ranging from 2% in mixed-humid climates to 9% in dry-hot climates.
- Over a 75-year service life, 3DP homes were shown to achieve total carbon savings of 2% to 6%, depending on the climate zone.

Embodied Carbon:

- The analysis compared the embodied carbon of the wall systems in both 3DP and STF homes. The 3DP system, which uses a low-carbon concrete mix and efficient wall designs, had a slightly lower embodied carbon than the STF system.
- The 3DP wall system featured a design that sought both material and performance efficiency, which contributed to reducing the overall carbon footprint.

Wall System Comparison:

- Monkman presented a detailed comparison of the 3DP and STF wall systems, highlighting how 3DP designs use vertical and horizontal reinforcement, open-cell insulation, and stainless steel z-ties to create a structurally sound and carbon-efficient wall system.
- The study focused on wall designs that were compliant with typical U.S. residential building codes, ensuring that the 3DP home could meet the same standards as STF homes.

Sustainability and Future Potential:

- Monkman underscored the importance of mix design in reducing carbon emissions, noting that larger aggregate sizes and increased aggregate-to-binder ratios significantly lower the carbon impact of 3DP materials.
- He highlighted that the industry is moving towards more sustainable practices, with commercially available 3DP mixes demonstrating lower carbon footprints than typical laboratory-scale mixes.

Industry-Wide Challenges:

- The presentation discussed the challenges of translating 3DP technology into real-world applications, including the need for scalable, pumpable, and buildable concrete mixes that balance sustainability with economic feasibility.

Conclusion:

- Monkman concluded that 3D printing can potentially reduce embodied and operational carbon emissions in residential construction, provided that efficient wall designs, low-carbon materials, and industry-wide standards are adopted.

Key Takeaways

- The potential of 3DP concrete construction to surpass conventional methods in sustainability is a promising prospect for the future of construction. The conclusion depends upon the 3d printable material, the wall design, and the printer operation.
- Through a literature review, it is understood that many mix studies are unsuitable for construction (inappropriate strength, uneconomic and unscalable mix designs)
- Few published mix designs have a lower carbon than generic 4000 psi ready mixed concrete.
- The industry uses more sustainable printable mixes than typically shown in research.

Available Whitepaper

For additional information, download the whitepaper titled here: "Reducing carbon emissions in the built environment: A case study in 3D printed home"

Session Q&A Transcript

The transcript of the Q&A session can be found in the Appendix: Appendix F: Sustainability Q&A

8. Breakout Session 2: Sustainability

In Breakout Session 1.2, participants focused on the role of sustainability in 3D printing construction, exploring how design choices, material selection, and standards impact the environmental footprint of 3D-printed structures. Teams were tasked with answering critical questions related to sustainable practices in wall design, the measurement of sustainability, and the influence of standards. Discussions highlighted the importance of optimizing material use, incorporating recycled and low-carbon materials, and minimizing waste throughout the construction process.

The session emphasized the role of standards in creating a consistent framework for sustainability evaluation, encouraging the use of alternative materials, and promoting global best practices. Key factors such as energy usage, waste minimization, and operational efficiency were identified as crucial for enhancing the sustainability of 3D printing in construction. The session also stressed the need for ongoing innovation and optimization to further improve the sustainability of 3D printing in construction.

How does wall design take into account sustainability when considering mortar vs concrete?

- **Material Choices:** Wall design must consider the choice of materials, such as cementitious material, coarse aggregate sources, and combinations of cementitious materials used per unit volume. Concrete often provides better mechanical properties than mortar, making it more suitable for some structural applications.
- **Optimization of Material Use:**
    - **Bead Dimensions and Aggregate Size:** The design should balance aggregate size and bead dimensions. Larger aggregates typically lead to larger beads and more material usage. Wall designs can optimize aggregate size to reduce the need for unnecessary material usage.
    - **Bead Thickness:** A thicker bead with appropriate aggregate sizes can support higher loads without overuse of material.
    - **Wall Thickness:** Wall thickness can be adjusted based on material use and structural requirements to improve sustainability, possibly increasing for coarse aggregates but optimized to minimize waste.
- **Structural Efficiency:** The design should aim for structural efficiency by using as little material as necessary, optimizing the load-bearing ratio to minimize excess weight and materials used.
- **Geometric and Topological Optimization:** Wall designs should incorporate geometric and topological optimization to reduce material usage and improve structural strength. This can reduce the overall environmental impact by minimizing the amount of material needed for the same structural outcome.

- **Sustainability Impact:** The design should take into account the sustainability of materials, including the use of recycled aggregates and alternatives to cement to reduce the carbon footprint.
- **Environmental Considerations:** Sustainability is influenced by the amount of shrinkage, durability, longevity, and how well the design accommodates future usage. Transportation distance and material availability should be factored into the sustainability assessment, with regional material sources prioritized to reduce the carbon footprint.

How do you account for sustainability, and if so, how do you measure it?

- **EPDs and LCA:** Environmental Product Declarations (EPDs) and Life Cycle Assessments (LCA) are key methods for measuring sustainability. LCAs can evaluate both materials and the overall structure, taking into account factors like carbon emissions, durability, energy usage, and material waste.
- **Energy Usage and Waste Reduction:**
    - **Material Production and Printing:** Sustainability metrics should include energy use in producing, transporting, and printing materials. The environmental impact of the printer system's energy use (e.g., kWh per square foot of printed wall) and the running cost/CO_2 footprint gained during the lifespan of the structure should be measured.
    - **Waste Minimization:** Efforts should be made to minimize waste during printing and material production. This includes accounting for waste produced by manufacturing processes and implementing practices to recycle materials wherever possible.
- **Embodied Carbon and Performance:** Embodied carbon is a critical measure of sustainability. This includes both the carbon footprint of materials and the energy used in the printing process. Reducing the embodied carbon per unit of material and optimizing the structural efficiency can improve the overall sustainability of the design.
- **Operational Considerations and Durability:** The sustainability of the structure also includes its operational considerations (e.g., energy use during system uptime, printer speed), and how long the materials will last without degradation. A structure that is more durable and resilient to environmental degradation will have a better sustainability profile.
- **Standards as Measurement Tools:** Adhering to established standards, such as ISO 14040-44 and EN15804+A2 (for European standards), helps provide consistent, comparable sustainability data. These standards can guide material choice, recycling processes, and energy usage calculations.

What role do standards play in sustainability?

- **Framework for Sustainability Evaluation:** Standards provide the foundation for defining and measuring sustainability in 3D printing. They offer guidelines for acceptable limits on CO_2 emissions, energy usage, and material performance. Standards also help quantify sustainability, giving the industry a shared method for comparison.
- **Uniform Tools and Processes:** Standards ensure that uniform tools and methods are used across the industry, helping to make sustainability assessments consistent and comparable. These standards can apply to various aspects of 3D printing, such as material selection, environmental performance, and manufacturing processes.
- **Benchmarking and Best Practices:** Consensus-based benchmarking through standards allows the industry to set performance targets and best practices for sustainable design. For example, standards for embodied carbon, load/weight ratios, and material longevity are essential for guiding sustainable construction.
- **Conformity and Certification:** Standards ensure that materials and processes conform to sustainability expectations. This is especially important when comparing products or systems that may have differing levels of sustainability. Tools like Tally databases, which rely on standard metrics, can facilitate more accurate and reliable assessments of sustainability.
- **Encouraging Sustainable Practices:** By mandating the use of sustainable materials and construction techniques, standards help promote sustainability within the industry. Standards can encourage the use of alternatives to cement, recycled materials, and reduced carbon impact designs.
- **Global Applicability:** Standards are essential for aligning different jurisdictions and markets on sustainability. Having global benchmarks allows different regions to adopt similar sustainable practices, which is particularly important for large-scale projects and cross-border developments.

What additional resources are available?

- Natural resources vs. economic resources, hard line to define.
- Suppliers should supply EPD

Additional Focus Areas & Topics

Participants were given the opportunity to submit additional topic ideas to discuss that were important to them, however due to limited time, these topics were not addressed.

- Best Practices and Guidelines:
    - Emphasizing the need for sustainability in construction practices through consensus-based benchmarking and best practice guidelines.
    - Establishing definitions for terms and boundaries and defining acceptable limits for CO_2 emissions per functional unit.
- Legislation and Standards:
    - The role of "Buy Clean" type legislation and environmental inhibitors to procurement.
    - Ensuring consistent standards for embodied carbon, durability, and long-term material availability across the industry.
    - Developing clear Product Category Rules for 3DCP systems with defined performance metrics.
    - The importance of universal standards, especially in underdeveloped regions, and the role standards play in maintaining conformity.
- Cost and Material Considerations:
    - The cost and CO_2 implications of building design decisions (e.g., wall thickness, insulation values).
    - Assessing mechanical properties, durability, and the role of low carbon concrete.
    - Sustainability of materials in terms of long-term availability, resource efficiency, and the importance of local sourcing.
- Lifecycle and End-of-Life Management:
    - Defining realistic scenarios for end-of-life, including deconstruction and recycling options.
    - LCA as a tool for evaluating the environmental impact from production to disposal.
    - Promoting longevity, resilience, and low environmental degradation of materials in structural designs.
- Operational Efficiency:
    - Measuring and optimizing logistics, maintenance, and repair processes to improve sustainability outcomes.
    - Resource efficiency, including water conservation and minimizing hazardous waste production.
    - Using uniform measurement tools to evaluate operational and printability efficiency.
- Data-Driven Approaches:
    - The need for consistent data across standards and metrics, such as in databases like Tally, to quantify sustainability.

  - Using tools and guidelines for measuring sustainability metrics such as energy consumption, hazardous waste, and water usage.
- Education and Consumer Awareness:
  - Educating consumers on the role of sustainability in green construction and resiliency.
  - Presenting 3DCP sustainability in ways that are transparent and understandable to the general population.
- Innovation and Optimization:
  - Encouraging continued optimization in material use, logistics, and sustainability metrics.
  - Promoting new technologies and methods for resource-efficient construction and sustainable design practices.
  - Implementing advanced solutions, like pumpability, mechanical performance improvements, and user-friendly designs.

9. Session 2.1: Safety, Equipment, Workforce, and 3D Printing Procedure

The presentation titled *Safety, Equipment, Workforce, and 3D Printing Procedur*e, delivered by Noah R Callantine, Jr, 3DCP Sales, Process Engineer & Field Service Specialist Concrete at Sika, emphasized the interplay between safety, equipment, workforce training, and procedural challenges in the field. He discussed the advantages and limitations of 3DCP, providing insights into the industry's current state and offering solutions to common challenges.

The presentation began by outlining the **key operational aspects** of 3DCP, including equipment requirements such as filling, mixing, pumping, and printing systems. Callantine highlighted the role of robotic arms and gantry printers in streamlining construction processes and ensuring precision. He stressed the importance of **proper material management**, noting that any post-mixing alterations, such as adding water or liquid color at the nozzle, can negatively impact the material's strength.

Callantine also explored the **construction industry's workforce challenges**, particularly the shortage of skilled labor. He emphasized that while 3DCP reduces the need for traditional labor, specialized training is still required to operate advanced machinery. The future of construction will depend on developing a workforce capable of handling new technologies, as much of the skilled labor pool is aging out.

He then discussed **safety protocols**, addressing the critical need for proper training and operational standards to prevent accidents. The presentation covered various **equipment needs**, from field sampling procedures to maintaining consistent material flow during printing.

Key Takeaways

- **Material Handling and Sampling**: Callantine stressed the importance of careful material management, mainly when dealing with large prints such as bridge girders. He emphasized that sampling should occur early in the process to avoid interfering with the print, which could induce weak points or cold joints. Sampling must be done without interrupting the flow of material, highlighting the complexity of balancing quality control and procedural efficiency.
- **Workforce and Training**: A significant portion of the presentation focused on the need for a trained workforce in 3DCP. As traditional skilled labor becomes scarce, construction companies must invest in training for new technologies. The Q&A revealed that one of the biggest hurdles is the lack of young, trained professionals to replace the aging workforce.
- **Field Equipment and Setup**: The presentation detailed the specialized equipment needed for 3DCP, including mixing and printing systems. Callantine emphasized that alterations to the material, such as adding liquid color at the nozzle, often reduce material strength. He recommended adding powder at the pump instead to maintain structural integrity.
- **Challenges of Local Material Sourcing**: Sourcing raw materials locally presents challenges, as consistency across different geographic locations is difficult to

achieve. Callantine explained that each site must be calibrated individually, with local sands and cements tested to ensure the correct formulation, which can be time-consuming and logistically complex.

- **International and European Standards**: The Q&A touched on the differences in how European countries have approached 3DCP standards compared to the U.S. Europe is approximately three years ahead in developing standards, having prioritized the technology earlier. However, U.S. standards remain fragmented, with Callantine noting that each region often wants to develop its own codes rather than adopting uniform global standards.
- **Future Applications**: Callantine highlighted that while smaller, novelty applications of 3DCP (like house columns) may not be practical now, they serve as proof-of-concept projects. Larger structures like homes and infrastructure will likely dominate the future of 3DCP as skilled labor shortages, and the need for efficient, scalable construction solutions become more pressing.
- **Sustainability**: Sustainability is a significant focus in 3DCP, with some projects reducing cement usage by up to 65%. However, transportation costs and the environmental impact of diesel-powered trucks present challenges that need to be addressed for 3DCP to achieve its full sustainability potential.

Session Q&A Transcript

The transcript of the Q&A session can be found in the Appendix: Appendix G: Safety, Equipment, Workforce and 3D Printing Procedure Q&A

10. Session 2.2: Canadian Standards Development

The presentation titled *Development of Canadian Standards for Additive Construction,* delivered by Marcos Silveira, Ph.D, Director of Engineering, Printerra, focused on the development of Canadian standards for additive construction. It highlighted the role of Printerra in advancing these standards and their collaboration with key research partners and institutions. The presentation covered the regulatory landscape in Canada, the importance of standardization, and ongoing research efforts, including completed projects like the one in Leamington, Ontario. The presentation also explored collaboration opportunities with the National Research Council (NRC) of Canada to standardize additive construction in Canada further. Additionally, the presentation addressed common gaps in the standardization of additive construction between Canada and the USA, pointing out that the development of standardized tests through ASTM presents a significant collaboration opportunity—the presentation concluded by advocating for cross-border collaboration in North America to harmonize standards for additive construction.

Key Takeaways

- **Advancing Standards:** Printerra is playing a crucial role in the development of Canadian standards for additive construction through collaboration with leading research partners.
- **Regulatory Landscape:** Understanding the Canadian regulatory framework is essential for successfully adopting and implementing additive construction technologies.
- **Importance of research in standardization:** Ongoing research efforts provide the empirical data needed to inform the creation of robust standards that can be universally applied across the industry.
- **Collaborative Opportunities with NRC:** There are significant opportunities to work with the National Research Council of Canada (NRC) to further the standardization of additive construction in Canada.
- **Cross-Border Standardization:** Addressing the common gaps in standards between Canada and the USA is key, with ASTM's development of standardized tests offering a prime area for collaboration.
- **North American Collaboration:** Harmonizing standards across North America through cross-border collaboration will be essential to the broader adoption and success of additive construction technologies.

Session Q&A Transcript

The transcript of the Q&A session can be found in the Appendix: Appendix H: Canadian Standards Development Q&A

11. Session 2.3: Exploring 3D Printed Real-Estate Perspectives: Opportunities and Challenges.

The presentation titled *Exploring 3D Printed Real Estate Perspectives: Opportunities and Challenges,* delivered by Dr. Julie Ann Hartell, Assistant Professor, Texas A&M, presented an insightful exploration into the current state of additive construction, specifically focusing on 3D-printed housing and its implications across various sectors. The presentation covered the perspectives of residential builders, real estate developers, and homeowners. It also examined the practical challenges and opportunities of 3D-printed homes, emphasizing cost savings, construction efficiency, and the evolving housing market. Dr. Hartell highlighted several real-world examples of 3D-printed housing projects, including collaborations between major players like ICON, Alquist3D, and Habitat for Humanity. Key topics included how 3D printing is reshaping the housing market, especially for Generation Z, and how government subsidies, evolving regulations, and emerging technologies are driving the industry forward.

Key Takeaways

- **Cost Savings & Efficiency**: 3D-printed homes offer significant cost savings by reducing workforce needs, construction waste, and project timelines. These savings have been particularly evident in collaborations like those with Alquist3D, which claimed up to 15% savings per square foot.
- **Market Shifts & Generational Demand**: With Generation Z showing a strong interest in affordable, sustainable homes, 3D printing technology is emerging as a viable solution to meet their needs. This demographic is expected to drive future housing trends, valuing innovative designs and sustainable practices.
- **Sustainability and Innovation**: The presentation stressed the importance of material choices and sustainability in 3D-printed homes. Projects like BioHome3D, which used biomass and recycled materials, were highlighted as examples of how 3D printing can support eco-friendly construction practices.
- **Challenges with Adoption**: Despite the advantages, public skepticism remains, with concerns over the practicality and cost-effectiveness of 3D-printed homes. Traditional builders and developers are also reluctant to adopt new technologies due to unfamiliarity with new methods.
- **Government Support & Regulatory Challenges**: Government subsidies and evolving regulatory frameworks are essential in promoting the development of 3D-printed homes. However, issues like mortgage adaptation, insurance coverage, and community planning regulations remain.
- **Training & Specialized Workforce**: The need for specialized training in 3D construction techniques was underscored. Electricians, plumbers, and other trades will need to adapt their skills to work within the framework of 3D-printed homes.
- **Case Studies**: Several real-world examples, such as ICON's 3D-printed housing developments in Austin, Texas, and BioHome3D's project in Maine, were highlighted to showcase the growing adoption of 3D printing in urban residential developments.

- This presentation provided a comprehensive view of the current state of 3D-printed housing, showcasing both the potential for growth and the hurdles that need to be addressed for broader industry adoption.

Session Q&A Transcript

The transcript of the Q&A session can be found in the Appendix: Appendix I: Exploring 3D Printed Real-Estate Perspectives: Opportunities and Challenges Q&A

12. Breakout Session 3: Standards Impact on Finance, Real Estate Development, Research Development, Commerce, Labor, and Safety.

Breakout Session 3 explored standards' multifaceted impacts on various sectors within the 3D-printed construction industry. Participants discussed how standards affect finance, real estate development, R&D, commerce, labor, and safety. The session provided a platform for participants to assess the positive contributions of standards and their challenges in ensuring the industry's growth and innovation.

12.1. Standards Impact on Real Estate Development & Financing

Positive Impacts:

Participants identified several key advantages that standards bring to the real estate and financial sectors. One of the most significant benefits is increased lender confidence, as standards enable multiple structures to be evaluated consistently, making comparisons easier for financial institutions. Similarly, insurance underwriters gain confidence that a 3D-printed structure has undergone proper quality control, reducing their risk exposure.

Another significant benefit is the reduction of community barriers, which allows developments to progress more efficiently, moving from concept to construction more quickly. Standards also help create baseline quality, leading to better financing options, which in turn helps mainstream 3D-printed buildings in the construction industry. Participants noted that faster construction times are achievable through standardized processes, which allow projects to be completed more quickly, and increased resiliency may provide better financing opportunities.

Additionally, standards were seen as a way to diminish risks for financial institutions and insurance providers and help buyers and financiers feel more confident in purchasing 3D-printed homes. Access to grant money and standardized pricing were also cited as potential benefits of having established standards in place.

Participants further noted that standards could help engineers feel more comfortable with 3D-printed construction methods, thus enabling developers to access financing earlier in the process. Finally, lower maintenance costs and design flexibility were seen as emerging opportunities for innovation within the field, potentially encouraging new developments in dense urban areas.

Negative Impacts & Potential Solutions:

While the positive impacts were clear, participants also voiced concerns about several adverse effects of standards. One of the primary challenges is that prescriptive codes could prolong the permitting process, causing delays and increasing costs. To address this issue, many participants suggested developing performance-based wall systems with pre-qualification standards that would help streamline the approval process.

Another concern raised was the higher costs associated with implementing standards. The potential for overdesign, which could unnecessarily increase material usage, was highlighted as a key issue. To mitigate this, many participants recommended encouraging the development of performance-based costs and standards to reduce overdesign and allow builders flexibility.

The learning curve for developers was also noted as a potential obstacle, with a few participants expressing concerns that developers may need help adopting and implementing new standards. To overcome this hurdle, many participants recommended ensuring that code language remains stable and adaptable, allowing policymakers to update standards without deterring developers.

Some participants also felt that standards may limit design creativity. To address this concern, many participants suggested that flexible language be incorporated into standards, allowing for both prescriptive and performance-based approaches.

A significant concern was that standards could restrict architectural design variability. Participants offered several potential solutions, including engaging architects and designers in the standardization process to prevent these restrictions and developing flexible design guidelines that allow for versatile sub-assemblies and pre-qualification processes.

Additional challenges included increased material costs due to overdesign and the potential for builders to be discouraged from adopting 3D printing if unfamiliar with the technology. To address these challenges, participants proposed various solutions, including industry subsidies to increase knowledge diffusion, introductory price breaks, and making standards widely available to increase familiarity among builders.

Sometimes, variable requirements from different Authorities Having Jurisdiction (AHJ) can create confusion and inconsistencies. Due to time constraints, participants were not able to brainstorm solutions for this issue. However, this issue remains an area for further exploration and discussion.

12.2. Standards Impact on Research Development

Positive Impacts:

One of the most significant positive outcomes identified by participants was the ability of standards to promote collaboration between industry, academia, and government agencies. This collaboration creates a unified research approach, helping align efforts and leverage shared resources.

Standards also enable the alignment of R&D efforts across the industry. Participants note that the use of common metrics helps build more usable literature and a stronger knowledge base, ultimately accelerating the development of new codes and standards. This alignment fosters faster and more reliable results, increasing confidence in the technology and enabling broader adoption.

Standards can further benefit research and development by catalyzing new research and opening up new avenues of exploration as the state of the art becomes easier to identify.

Standards help kick off a feedback loop where ongoing research informs better standards, leading to more research and innovation. This process also helps increase the Technology Readiness Level (TRL), driving more interest and investment in 3D printing technologies.

Participants identified additional positive impacts, including making it easier to compare field results and helping guide R&D to confirm the durability standards for 3D-printed structures. Participants also recognized that standards allow for innovation and solutions that are performance-based and not prescriptive, giving researchers flexibility in their approaches.

Negative Impacts & Potential Solutions:

Despite the many advantages, participants highlighted several challenges related to standards in research and development. A key concern is that standards could artificially constrain research to fit within guide rails, limiting the scope and creativity of R&D efforts. To mitigate this challenge, participants agreed that collaboration between industry and research be prioritized to ensure that research continues to inform and evolve codes and standards.

Another challenge raised by participants was that research often outpaces standards, which can result in the latest innovations needing to be fully captured within existing guidelines. To address this, many participants once again recommended collaborating between industry and research to keep standards up to date with the latest findings.

Additionally, participants noted that R&D efforts must test beyond what current standards allow, which can create roadblocks to innovation. The same solution—a collaboration between industry and research—was proposed to ensure that new findings are integrated into the standards.

Another concern was the slow pace of change in standards, with many participants noting that once in place, standards can be difficult or slow to change. For standards to work effectively, many participants stressed the importance of having good representation in the codes and standards issuing bodies and collaboration across industry, academia, and government. They also recommended potentially shortening revision cycles to accommodate the rapid advancements in 3D printing.

Another hurdle discussed was that standards often require special and expensive equipment inaccessible to everyone. Many participants recommended that standards be designed to be practical and not cost-prohibitive, ensuring wide industry participation.

Finally, participants noted that current practices may impede technological advancement, although due to time constraints, no specific solutions were discussed in this area.

12.3. Standards Impact on Workforce and Labor

Positive Impacts:

Standards in 3D-printed construction were widely seen as a way to alleviate labor shortages by streamlining processes and creating new opportunities for skilled workers. Additionally, standards can enable other trades to work more easily within 3D-printed construction projects, addressing current uncertainties in how different trades fit into the process. This, in turn, can improve the skill set of willing labor, allowing workers to adapt to new technologies and methods.

Another key benefit is that on-site training improves quality control (QC) by ensuring workers are familiar with the specific requirements of 3D-printed construction. Standards also allow for standardized training programs that promote worker mobility between employers, making it easier for skilled workers to transition between jobs.

Participants highlighted that standards could incentivize tech-savvy younger generations to enter the construction industry, which has traditionally struggled to attract new talent. By making the industry more appealing through integrating new technologies, standards can also extend the longevity of the workforce, reducing the physical strain typically associated with construction work.

Standards were also seen as enabling the creation of new jobs in areas like technology and quality control. The upskilling that comes with adopting new standards can result in a more skilled and capable workforce equipped with the training necessary for safer job sites and better personal protective equipment protocols.

Moreover, participants noted that standards can help catalyze the labor force into a true trade, building a more professionalized workforce. This perspective aligns with the goal of fostering new opportunities through education and training, encouraging more workers to enter the field, and expanding the pool of qualified labor.

Negative Impacts & Potential Solutions:

However, participants also discussed several challenges. A major issue identified was the high cost of training programs needed to adapt workers to the new standards. The participants viewed these costs as a significant burden, particularly for companies that need to implement widespread training initiatives. To address this, participants recommended several solutions, including developing standardized training programs to help lower costs and trade school partnerships that could pool resources from multiple companies. University partnerships and labor union collaborations were also suggested as ways to leverage existing infrastructure and funding for training.

Another concern was the potential for standards to become an issue if they were not machine-agnostic, meaning workers would need to learn specific systems for different brands or technologies. To counter this, participants proposed creating general training programs that could be applied across machine and material types, ensuring that standards are not tied to any specific manufacturer and focus on essential processes.

Participants also raised the potential for lost jobs through automation. However, participants believed that standards could help increase job availability by formalizing new roles and expanding the industry's labor needs. Participants also noted the issue of decreased print speeds due to limits on worker proximity to moving equipment. A solution offered was to use remote sensing technology to track worker movements and perform tasks remotely, reducing the need for human intervention near operating machines.

Also of concern was the resistance to learning new skills and increasing skill gaps, especially as the industry evolves. To address this, participants recommended incentivizing learning initiatives and emphasizing the growing demand for specialized skills in 3D-printed construction. Similarly, the worry that standards may decrease the need for extra labor was discussed, with participants suggesting retraining initiatives to help workers stay relevant as technology changes.

Concerns around job displacement and the need for retraining were also raised, particularly in cases where skills are highly specialized and only applicable to niche roles. The differences in skill sets required for traditional construction versus 3D-printed construction were noted as a potential barrier, with participants recognizing that companies might hesitate to invest in additional labor due to these disparities.

Finally, participants noted the risk of economic inequality as a barrier to learning new skills, with the potential for standards to force training that could increase inequality without proper incentives. Although the participants discussed no specific solutions, they did identify that the need to ensure accessible and equitable training opportunities was highlighted.

12.4. Standards Impact on Safety

Positive Impacts:

Safety was a top priority for the group, with participants emphasizing that standards for operation and structural considerations can prevent injury and death. Ensuring safety in 3D-printed construction is paramount, as a construction-related injury or death would severely impact the industry's credibility. Standards also allow for enhanced safety protocols, incorporating advanced measures to reduce on-site accidents and improve labor safety.

Participants noted that standards can help promote a safe working environment, particularly through operator certification. By ensuring that workers are properly trained to operate 3D printing machinery, job site risks are significantly reduced. Standards also encourage the proper disposal of waste material and site-specific geometry, which can reduce hazards and improve accessibility, further enhancing safety protocols.

From a structural perspective, standards are essential for ensuring the safety of building occupants. Participants highlighted that adhering to established standards can improve the safety of a printed structure. Moreover, standards can reduce overly conservative designs, ensuring that designs are appropriately conservative without overusing materials, which can save costs while maintaining safety.

Finally, participants recognized that 3D printing methods could reduce job site safety accidents during the printing process and help weed out bad actors by enforcing strict safety requirements. While the group acknowledged that improvements to the safety of structures are still being made, they affirmed that standards are critical to making the industry safer for workers and building occupants alike.

Negative Impacts & Potential Solutions:

Despite these positive outcomes, participants also highlighted some challenges associated with safety standards. One concern is that safety standards can produce a false sense of security, leading workers or supervisors to assume all risks are mitigated. To address this, many participants suggested that the scope of safety standards should be articulated, outlining what they do and do not cover. For example, job site safety and the long-term safety of the building structure should be distinct areas of focus, and standards should ensure that no gaps are left unaddressed.

Another concern was that safety standards could be used as an excuse not to apply common sense in certain situations. Many participants recommended that standards be simple and practical and written at an appropriate level for the intended audience (e.g., researchers or installers).

One more complex issue was the potential for overdesigning safety features, which can result in unnecessary material use and increased costs. To address this, participants suggested that more R&D would help lower future costs by reducing the need for over-conservatism in safety designs. They also proposed regional design requirements to account for local environmental factors, such as seismic activity, which require more conservative designs.

Participants stressed that design conservatism should be proportional to the criticality of the designed structure and balanced with the end use and environmental exposure, such as seismic risks.

The time and cost required for training were also discussed, with concerns that increased training requirements could raise initial costs for companies. To address this, participants suggested creating project thresholds that trigger the need for training and certification based on the scale or complexity of the project. They also recommended developing levels of training for specific project requirements, ensuring that operators are trained to the appropriate competency level based on the needs of the job.

12.5. Standards Impact on 3D Printing Procedures

Positive Impacts:

Many participants identified one major benefit: Standards can reduce building permit time and planned review processes, helping projects move forward more quickly. Standards were also seen as a way to improve sustainability by reducing waste material during construction, an important consideration as the industry moves towards greener practices.

Another positive impact is that standards allow new companies to enter the industry quickly. By providing clear guidelines, standards reduce uncertainty for startups and help them navigate the regulatory landscape more easily.

Participants noted that standards improve quality assurance and control (QA/QC), ensuring that 3D-printed structures meet consistent quality benchmarks across the industry. Additionally, standards allow for safety standard procedures across the industry, ensuring that safety protocols are followed uniformly.

Using standards also enables builders to keep detailed records during printing, which helps with project documentation and accountability. Standards further facilitate after-print modifications by trades, making it easier for other professionals to work with 3D-printed structures after the initial construction phase.

Participants recognized that standards ensure consistent results, which is crucial for the credibility and reliability of 3D printing as a construction method. There was also a noted benefit of standards offering procedural recommendations that could help mitigate potential litigation.

From a technological perspective, participants highlighted that 3D printing allows for high precision and complex, customized designs, which would be difficult or impossible to achieve using traditional methods. Additionally, 3D concrete printing can significantly reduce construction time compared to conventional methods, with automation allowing for continuous operation and faster project completion.

Negative Impacts & Potential Solutions:

Despite the numerous advantages, participants raised concerns about the potential for standards to stifle innovation in materials, as rigid guidelines may limit the ability to experiment with new materials. To counter this, many participants suggested making standards flexible enough to accommodate innovation by providing both prescriptive and performance-based pathways to allow creative solutions while maintaining safety and quality standards.

Similarly, participants expressed concerns that existing standards and protocols could stymie innovation and limit recommendations for field procedures. To address these issues, they again advocated for a flexible approach to standards that allows for innovation while ensuring compliance and consistency.

Participants also discussed whether total wall thickness should be part of a design standard or guidance, reflecting the ongoing debate about how prescriptive standards should guide design choices.

Standards can also impact innovation more broadly, with many participants noting that overly rigid standards could slow the adoption of new procedures and materials. They proposed several solutions, including creating a section in standards for performance-based testing, allowing innovations to prove their equivalency to existing standards while keeping the door open for new methods. They also recommended limiting the scope of the standard and supplementing it with guidelines to allow for more flexibility in implementation. Additionally, the group suggested that a consortium could develop initial standards to allow for gradual changes in construction industry standards, acknowledging that large-scale changes take time. Finally, they advised that standards should only include critical safety requirements, ensuring that essential safety elements are addressed without over-regulating non-critical areas.

Some participants also raised concerns about how existing standards could increase costs or slow the adoption of innovative new procedures if introduced after established standards. They cautioned against letting standards govern job site means and methods, which could stifle flexibility and adaptability in the field.

Another challenge discussed was the potential for confusion in the industry due to different procedures for different printing systems. The need for greater clarity and uniformity in how different systems are handled was noted as an area that could benefit from further standardization efforts.

Session Q&A Transcript

The transcript of the Q&A session can be found in the Appendix: Appendix J: Breakout Session 3: Standards Impact on Finance, Real Estate Development, Research Development, Commerce, Labor, and Safety.

13. Appendix

13.1. Appendix A: Agenda

Tuesday, August 20, 2024	
8:00 a.m.	Welcome Remarks • NIST Introduction • NCCoE: Overview of the Center • Workshop Purpose & Deliverables
	Session 1.1: Intro: Progress & Lessons Learned Presenters: • Shawn L. Platt, Ph.D. • Eric L. Kreiger, PE • Stephan Mansour
	Session 1.2: State of the Industry and Challenges it Faces Presenter: Bing Tian, Ph.D.
	Break
	Session 1.3: Printing Formats and Challenges to Standardization Presenter: Eric L. Kreiger, PE
12:00 p.m.	Lunch & Networking
1:00 p.m.	Breakout Session 1: Hurdles to Field Printing
	Session 1.4: Sustainability Presenter: Sean Monkman, Ph.D.
	Breakout Session 2: Sustainability
4:15 p.m.	Review, Final Thoughts & Closing - Day 1
5:00 p.m.	Adjournment

Wednesday, August 21, 2024	
8:00 a.m.	Welcome Remarks - Day 2
	Session 2.1: Safety, Equipment, Workforce and 3D Printing Procedure Presenter: Noah R Callantine
	Session 2.2: Canadian Standards Development Presenter: Marcos Silveira, Ph.D

	Break
	Session 2.3: Exploring 3D Printed Real-Estate Perspectives: Opportunities and Challenges. Presenter: Julie Ann Hartell, Ph.D.
	Breakout Session 3: Standards Impact on: Finance, Real Estate Development, Research Development, Commerce, Labor, and Safety.
	Workshop Close Day 2 & Next Steps
12:00 p.m.	Lunch & Networking
1:00 p.m.	NCCoE Tours
	ACE Consortium Meeting (Members Only)
	ASTM F42.07.07 Meeting 1 (All are welcome)
5:00 p.m.	Adjournment

13.2. Appendix B: Presenter Bios

Shawn L. Platt, Ph.D.
Research Civil Engineer
National Institute of Standards and Technology (NIST)
Shawn.platt@nist.gov

Dr. Shawn Platt is a Research Civil Engineer at the National Institute of Standards and Technology (NIST) within the Infrastructure and Materials Group of the Materials and Structural Systems Division. He is the Project Lead for the *Additive Manufacturing with Cement-based Materials* project at NIST, Lead for the Additive Construction by Extrusion (ACE) Consortium and is responsible for all the structural and material investigations for the *Reliability of Fiber Reinforced Polymer (FRP) Composites in Resilient Infrastructure* project.

In addition to Shawn's current roles, recent research concentrations have focused on carbon capture and carbonation of cementitious materials, bio- and waste-based construction materials, and disaster resilience of masonry structures with a view of delivering lifelong sustainable structures and communities. Interdisciplinary and international research interests have broadly focused on novel retrofitting and rehabilitation materials and methods with concentrations in non-traditional construction materials, vernacular architecture, and material interactions in complex systems as well as socio-economic impacts and policy development. Shawn's brings over 25 years of construction experience to support his academic and research career providing a unique perspective to projects.

Aron Newman
Division Chief
National Institute of Standards and Technology (NIST)
aron.newman@nist.gov

Dr. Aron Newman is the Chief for the Materials and Structural Systems Division (MSSD) of the Engineering Laboratory (EL) at NIST. Previously, he served as the Leader of the Infrastructure Materials Group in the same division. Prior to joining NIST, Aron worked at Booz Allen Hamilton and supported technical program management of projects involving cement, batteries, fuel cells, permanent magnets, and polymer membranes at the Advanced Research Project Agency – Energy (ARPA-E) with the Department of Energy.

Eric L. Kreiger, PE
Researcher and Chair of ASTM 564-OB (Structural Design and Testing)
U.S. Army Engineer Research and Development Center (ERDC)
Eric.L.Kreiger@usace.army.mil

Stephan Mansour
Associate Consultant
ASTM International, Wohlers Associates
smansour@astm.org

With almost two decades of experience in construction, Stephan's specialty is construction digitization and leading disruptive innovative additive construction (AC) adoption. As part of Wohlers Associates powered by ASTM International, Stephan advises global corporations and entrepreneurial establishments on the successful implementation of AC. Emphasis is on meeting organizational objectives and addressing construction sector pain points.

Stephan is currently leading the International Additive for Construction Standard initiatives as the Chair of ASTM's F42.07.07 - Construction and co-convenor of ISO/ASTM - JG80. His recent milestones include the publication of ISO/ASTM standard 52939 on Additive Construction and leading ASTM efforts in the publication of the Advanced Technologies for Digitalization of Construction Industry Roadmap as part of the NIST Advanced Manufacturing Technology Roadmap (MFGTech) Program.

Bing Tian, Ph.D.
Director of Research and Development
Quikrete Companies
bing.tian@quikrete.com

Bing has over 25 years of experience in the concrete and construction industries. He is an expert in new cementitious binders, concrete durability, 3D concrete printing, sustainability, construction products for infrastructure, masonry mortars and stucco, and other dry-mix cement and concrete products. He is an active voting or consulting member for many ACI, ASTM, and ICC technical and certification committees.

Bing is currently the material group leader for the ICC-IS-3DCT Committee. He holds a Ph.D. degree in Civil Engineering Materials from Purdue University.

Sean Monkman, Ph.D.
Vice President, Materials Science
ICON
smonkman@iconbuild.com

Sean Monkman is the vice president of materials science for ICON, a construction technologies company that uses 3D printing robotics, software, and materials to advance humanity. Sean oversees the research of concrete materials, innovation, and commercial 3D printing technology support.

Before joining ICON, Sean was the senior vice president of technology development for the cleantech concrete company CarbonCure Technologies. He oversaw the company's research and intellectual property to develop scalable carbon utilization technologies to create more sustainable concrete. He was the technical lead on the firm's winning effort in the NRG COSIA Carbon XPRIZE.

Sean holds a PhD in Civil Engineering from McGill University. His career has included more than 25 years\ working in sustainable concrete materials. Sean has authored over 100 papers and presentations on sustainable concrete and is a co-inventor on over 130 issued and pending patents related to the work. He was recognized as the Mission Innovation Champion for Canada at the Fourth Mission Innovation Ministerial (MI-4) in 2019. Sean served a six-year term as chair of the 130 committee on Sustainability at the American Concrete Institute.

Noah R Callantine, Jr
3DCP Sales, Process Engineer & Field Service Specialist Concrete
Sika
callantine.noah@us.sika.com

Noah Callantine is a 3D Concrete Sales and Equipment Specialist with extensive expertise in the additive construction market. Based in Pennsylvania, Noah is responsible for sales, customer training, equipment setup, product testing, and development. He holds a patent and has developed multiple pieces of equipment tailored for the 3D construction industry. Over the past four years, Noah has been a pioneer, playing a pivotal role in building the 3D printing market across the United States and internationally, including in Brazil, Canada, Morocco, Peru, and ongoing projects in Mexico.

Noah's career spans over two decades, with significant experience as an International Field Service Manager at Putzmeister / Allentown Shotcrete, where he spent 20 years teaching clients the operation of specialized equipment and the application of materials. His global experience covers a wide range of sectors, including shotcrete, tunneling, mining, refractory, repair mortars, and concrete placement. His project portfolio includes high-rise buildings and tunnels in New York, major infrastructure projects such as the Panama Canal, hydroelectric dams in India and Bhutan, and refractory installations across Asia, Europe, and South America.

With a strong background in fabrication, welding, electrical, and mechanical engineering, Noah brings a hands-on approach to his work in 3D concrete printing. Since joining Sika in 2019, he has focused on advancing 3D construction printing (3DCP) technologies and continues to push the boundaries of innovation in this field.

Marcos Silveira, Ph.D
Director of Engineering
Printerra
msilveira@printerra.ca
Marcos Silveira is a specialist in the design of reinforced and post-tensioned concrete structures, as well as additively constructed (3D-printed) structures, utilizing BIM and FEA-based tools. Currently serving as the Director of Engineering at Printerra 3DCP, Marcos holds a Ph.D. in Structural Engineering. His career includes significant academic contributions, including teaching and research roles and publishing numerous research

papers in esteemed journals. Marcos has been a key figure in designing and managing most additive construction projects across Canada. As a member of the ISO TC261 JG80 & ASTM F42 Group, Marcos was instrumental in creating the ISO/ASTM 52939 standard for additive construction and now leads the WK84415 work item on evaluating structural printed elements.
Julie Ann Hartell, Ph.D. Assistant Professor Texas A&M julie.hartell@tamu.edu In the fall of 2020, Dr. Julie Ann Hartell joined the Department of Construction Science, housed in the College of Architecture, as an assistant professor. Her expertise lies in construction materials, specifically concrete materials. Her current work emphasizes recycling strategies and sustainable material design, the characterization of material performance at both the material and system scale and developing building innovations for affordable and sustainable housing.

13.3. Appendix C: Progress & Lessons Learned Q&A

Q: 3D-printed structures open up significant opportunities for structural efficiency through geometric optimization. One of our concerns is how much variation in system geometry would be possible for a validated/certified system without triggering the need for additional system testing. Do you anticipate rigid standards emerging to address this scope/coverage question? Additionally, do you anticipate that validated FEA models could be used to broaden the scope of what geometries would be covered under a suite of system-level tests?

A: We do anticipate rigid standards emerging. There will be approved methods using unique geometry, and approved models are expected. Eventually, there will be a valid methodology to design, allowing for geometry changes while using the same level of technology. There are still many questions about structural performance, but appropriate guidelines will be developed.

Q: Do you foresee emerging standards for on-site 3D-printing of structural concrete elements being applicable to off-site printed structural elements as well? Or do you anticipate a separate set of standards for these?

A: The goal is to make them the same standard.

Q: How can ICC, ACI, ASTM, and NIST coordinate efforts to promote consistency across the industry, holistically identify gaps, fill those gaps, and reduce duplication of efforts?

A: Coordination through a consortium is crucial. We need a mechanism that allows us to protect our interests while still moving the industry forward. By sharing global data and having a platform for communication, we can ensure that our efforts are aligned. Attending workshops like this one helps bring the messaging forward as we return to our respective organizations and committees, fostering a larger community.

Q: Is there any information on the standardization for structural design and building that Eric mentioned?

A: The ACI reports on structural design have not been completed or published yet, but they should be ready soon. We need help getting these completed. Several structural engineers are working on building these guidelines. ACI and ICC are working on aligning the information and guidelines. The work is in progress, and the guidelines are expected to be ready in approximately one year.

Q: Is there any ongoing building or small structure that could be studied and used as an "exhibit" to show positive results using the new technology?

A: Yes. Shawn will try to gather more information on this and include it in the report. There are plans at NIST to construct small-scale structures. These efforts are in progress at several different levels.

Q: There is often reluctance to adopt new technology. Are there any government proposals to use additive construction in the modernization plan for infrastructure?

A: This is a tricky question. There are no specific plans, as we cannot show bias toward one technology. It's important for additive construction (AC) to compete with existing technology. AC can align with modernization, such as reducing CO_2 emissions in the Army, but it must be cost-competitive. Standardization will help make the cost competitive, which will, in turn, allow for more modernization. This is being investigated at different levels of the federal government.

Q: What kind of testing methods (fresh-state or cured) have been accepted and used for ACE?

A: Several testing methods are under investigation, but none have been finalized or are currently being used. There is no finalized standard yet.

Q. What is Stephan's info to get the report?

A: The report is available here. For more information, you can contact him at smansour@astm.org or through his LinkedIn profile.

13.5. Appendix D: State Of The Industry And Challenges It Faces Q&A

Q: In addition to measuring W/C cement ratio, what has been your experience in measuring viscosity during printing?

A: W/C is not enough to monitor the material, especially when longer hose segments are used and in extreme working temperatures. We do talk with our partners, and they are looking into some viscosity sensors to inject into the pipeline. So far, they're working on that, but I don't think it has been successful yet. Without that sensor, we recommend using flow testing—bringing a flow table to the job site, mounted on the base, so you can check the flow of the material coming out of your printing head.

Q: Why haven't we been able to manage this quality successfully?

A: I'm not a hardware engineer, so I don't have the answer. We're working with our partner on this technology, and so far, the feedback has been that they haven't been successful. I'm more focused on the material side as a chemist by nature.

Q: Is the current technology industrial enough?

A: A lot of what we're seeing outside is not robust yet. Manufacturers are still working on it.

Q: What type of sensor is used for W/C measurement?

A: I can provide you with the answer after the meeting. I have a website I can refer you to. It's commercially available, so I'll just refer you to it.

Q: How do 2K admixtures affect printability and performance?

A: The reason I like the 2K system is because you have a base material, and then you can adjust your admixture dosage on site or off site. It provides flexibility, like adding more retarder for hot weather or tweaking water reducer content based on aggregate moisture. The best way to do 2K is batch mixing, which is easier. Continuous mixing, where you inject at the printing head, presents challenges like dosing precisely and mixing the admixtures into the base materials in a short time and in small mixing chamber. The results have not been consistent, and the technology is not yet mature for job site use.

Q: Do you see the prepackaged 3D CP cost coming down?

A: That's a business question. I can say that with the growth of this industry and more production, it's possible. Right now, it's made to order with no inventory. But in the future, yes, costs could come down as we have more volume.

Q: How is pre-qualification for material currently handled?

A: Currently, it's confusing whether the contractor or the engineer approves the material. The ICC standard we're working on will require materials—whether field mix, ready mix, or prepackaged—to meet specific standards and be submitted to a third testing lab for pre-qualification.

Q: Do you see the customization aspect of 3D CP as advantageous compared to, for example, CMU systems?

A: Yes, 3D printing offers the ability to create shapes, contours, and curves, which CMU cannot. While 3D printing is often suggested for low-income housing, I see it more as a solution for markets that require complicated shapes or structures, like offshore drilling platforms or precast units. It's a solution for specific, often richer, markets rather than cheap applications.

Q: How does the US industry compare with European and other international sectors?

A: The US is more risk-taking and aggressive, moving faster than the rest of the world. While Europe and the Middle East have projects going on, I see more success stories in the US, likely because I'm local, but also because the US is moving quickly in this area.

Q: Do you think 3D CP's ability to create optimized structures and use less material is enough to offset the cost difference compared to CMU?

A: It's very possible, but we need real case studies and cost analyses to confirm this. The 3D CP industry is still new, and while CMU is mature with well-known costs, 3D CP needs to be evaluated on a larger scale to determine cost efficiency.

Q: As a supplier, before you sell the product to a contractor, what steps are taken by Quikrete to ensure your customers fully understand the true material challenges?

A: The first step is conversation and education. We want to understand what you need and work with you throughout the process, not just sell you the material. We prefer to work with customers who are open to collaboration. If a customer's printer system isn't good enough, we might choose not to do business with them. We focus on supporting you throughout the process because your failure is our failure.

Q: What is the aggregate size used in ultra-high performance concrete (UHPC)?

A: UHPC uses fine aggregates. UHPC is a niche market for very special applications, and we don't focus on it because of its small volume. In the new ICC standard, we differentiate between mortar and concrete, including shrinkage requirements, which are a key performance characteristic. While UHPC can achieve certain shrinkage levels, it's very expensive—several thousand dollars per cubic yard—making it less practical for most applications.

Q: How can we tackle the dry mix temperature problem, especially when the material is at a job site with temperatures greater than 85-90°F?

A: The solution is to use a chiller. You measure the temperature of your dry mix, water, and the mixed materials. With a chiller, you tweak the mixing water temperature to keep the mixed material temperature constant. Chillers help compensate for the high or low temperature of the dry mix to ensure consistent results.

Q: What is Quikrete's strength compared to UHPC?

A: Quikrete 3DCP typically achieves 5000 psi, while the new ICC standard specified the minimum concrete printing strength requirement is 2500 psi. While UHPC allows for higher strength, such as 15,000 psi and it can reduce the load loading area and thus reduced material usage, however, it's much more expensive. The cost analysis often doesn't justify using UHPC, given its high price.

Q: Do you think focusing on prefabrication is a wiser first step into advancing the 3D CP industry?

A: Yes, I agree. Prefabrication is a good approach, especially when dealing with more complicated shapes or reinforcement challenges.

Q: Can you share any lessons learned from failures in the industry?

A: One notable failure was the demolition of a 3D-printed house last year due to quality control issues. The failure resulted from improper curing and testing of materials, leading to a structure that didn't meet strength requirements. Moving forward, standards and proper on-site testing will be critical to avoid such failures.

Q: Can you talk about the machinery or systems needed to manufacture one of those frames illustrated in the right-side picture?

A: The frame was printed layer by layer and then flipped. This was done for a sculpture at the Coachella Festival. While similar techniques could be used for printing columns or beams, there are challenges, especially with reinforcement and structural integrity, that the technology hasn't yet solved.

Q: What's frustrating about the challenge of supply chain and contractor field data not being shared for necessary adjustments?

A: The lack of data sharing is a significant issue because we don't yet have a formal association to collect and share information. Thanks to the consortium, we are beginning to address this by sharing data and working together. However, there's still reluctance due to IP concerns, which we must overcome to grow the industry.

Q: How would design qualification work with proprietary designs and admixtures?

A: If you design your mix on the job site, you are responsible for it. We don't disclose our mix designs or formulas because they involve significant investment. We also don’t allow anyone to modify our products on-site due to liability concerns. Accountability is crucial, and we provide warranties that require us to maintain control over our products.

Q: Do you see standards being needed or introduced in the near future?

A: Yes, standards are coming. The ICC standard, potentially numbered 1150, may be published within a year and a half. ASTM is also working on guidelines, though more detailed specifications are needed. Over the next year or two, we should see more guidelines and specifications emerging.

13.6. Appendix E: Printing Formats and Challenges to Standardization Q&A

Q: Do you see the difference in failure modes for 3DCP (e.g., due to the anisotropy introduced by print layers) creating a need for different types of tests of structural elements that aren't currently in place for cast concrete? Any sense of what these might be?

A: Regardless of what material is used, the loading conditions are very similar. Actual procedures change based on material, reaction, speed, etc., but the actual tests don't change that much. Refer to the list of tests from the transcript.

Q: Does ERDC anticipate doing any design-printing-testing of 3DCP beam elements consisting of multiple segments (for longer spans) (reinforced or post-tensioned)?

A: Yes.

Q: For the blast test, you mentioned a beam. Is this a ring beam, or are you referring to the lintel over the door?

A: We had lintels over doors and beams every 4 feet on center that were connected to the walls through grouted cavities.

Q: Guam is a seismic zone #4. How do you design to accommodate this?

A: It was demonstration, so we did not. The test structure that was built was a baseline design with no consideration of seismic or weapons effects. The purpose of the demonstration was to train military personnel to use the equipment and then to test the baseline design against blast. All the designs we have done to date are for research purposes. However, we are currently looking into designing for seismic regions C and higher.

Q: How do you see the potential of using non-destructive testing methodologies for QA/QC, such as Pulse velocity?

A: Great for doing QA/QC. We may not have it available for deployed construction, but it's useful for everyday technologies.

Q: How do you view the standardization process for the fabrication of roofs/vaults?

A: When doing roofs, we have pockets that we connect, tying everything together. We had reinforcement into the wall and into the roof. There are other methodologies. You can build an item sideways an tilt by 90 degrees. You could do overhangs as long as your material curing rate is quick enough. It's a little more complicated. You would have to have an incorporated grouted cell.

Q: If extracting samples from printed elements is difficult and onerous, can the industry accept a cast specimen strength along with a scaling factor to stand in for the strength of the structure?

A: Currently, in the state we are at now, we need to better understand what that scaling factor is. Is it extreme? Is it 25%? This is something we need to further understand. We will want to make sure we have field data to feel comfortable that the structure meets requirements. We use test samples for quality control. Strength is reliant on the form that is built. We may get to a better understanding based on inputs; however, it might be 5-10 years from now. Understanding is a barrier right now.

Q: If you don't want to use sensors for expeditionary applications, how are you providing quality control for the printing process?

A: We are using the unconfined compression test and flow table throughout the process to make sure materials meet requirements. We understand ranges based on material. We have a publication based on the Guam field testing equipment. We monitor before placing it, at the nozzle, and after we clean out the pump and get ready to start again. Based on how the material is performing after extrusion we may make minor adjustments to proportions.

Q: What has been your experience in terms of structural performance test results in different structural wall typologies (straight, pilaster, chevron)? How have FEA results compared with testing results?

A: In general, the walls, if designed properly, can meet strength requirements, and due to stress concentrations at interfaces the walls have more ductility than conventional methods, but the design is not a 1-to-1 comparison. Chevron walls and pilaster walls have better out-of-plane strength than a straight wall, but straight walls have slightly better in-plane strength. We do have a qualification for beams and walls developed based on FEA analysis. You have to account for the interfaces, which increases the complexity of the models. After verifying the model based on testing, we have continued to get comparative results.

Q: What is the size of a typical print team with respect to a DOD application?

A: It depends on what system you are using. We are technology agnostic—if we can use a system, we will use it. We have used mortar systems. The type of mixture/printer is whatever is available. We are not set on any particular printer and will depend on what the DOD wants to use. It can take from 2 people (quality control, feedback) on a mixer/pump mortar system to up to 8 people on a larger operation. We usually use 4 people. Typical printing requires 4 people: one for mixing, one controlling the speed of the pump, one controlling the speed of the printer, one doing quality control, and a site lead.

Q: What type of printing system have you deployed for the examples shown in your presentation? Can you go over more on the challenges encountered during printing in the field, such as equipment, materials, team members, etc.?

A: We typically use a gantry system developed specifically for deployments that has easy to replace parts, obtainable from a local hardware store, and a materials delivery system that uses locally available materials, but if there is another system that meets these requirements, we are open to using it. It's more about the process, not the printer. We faced challenges like hot weather, humid weather, and exhaustion. Most of the challenges are on materials and the limits of the material delivery systems. We have developed training that goes over adjustments If you see this in the mix, this is what you can do. Pump cleanout is important as it's the pinch point.

Q: What were the design considerations for the connections of beams and walls for the multi-member system you showed at the end of the presentation?

A: Answered in the previous question.

13.8. Appendix F: Sustainability Q&A

Q: One of the major data gaps in LCA modeling of building construction is the A5 impacts from on-site construction/installation, which are handled only as lump sum inputs in Tally, thus requiring contracted data collection. Do you have a sense of how these impacts would compare to traditional home construction? Could the data be shared anonymously with LCA data methods aggregators like Fed Commons, CLF, Building Transparency?

A: Thanks for the question. The co-authors of the white paper agree on this point. The expertise on that particular answer is not in my hands; one of my colleagues is the lead on the lifecycle calculations. We agree with the difficulty of coming up with this A5 data, as we've looked into it ourselves. We've published a white paper and developed a version that could go into a journal and explore the topic in more detail. We would look at publishing the dataset we collected for the 3d printing process for transparency. We're trying to get the data out there where it's useful. But the topic and details of A5 LCA impacts is under explored and I'm glad people are identifying this issue.

Q: Have you looked into sustainability of 3DCP for non-residential projects, infrastructure, industrial buildings, etc.?

A: No. To date, our business has focused on residential projects, not on things like windmill turbines or other infrastructure. We've done a band shell in Austin, but largely it's been houses for people. I think the conclusions from the analysis of residential construction could scale to other types of additive construction depending on the mix design and the printer and the details of the business and usual comparison. It's worthwhile for someone to look at this, for example there are companies creating 3DP concrete wind turbine bases, water tanks, coastal reef structures. Is 3DP printing a more sustainable way to make these items?

Q: Any comments on ICF (Insulated Concrete Forms) homes versus 3DCP housing on sustainability?

A: ICF was outside our model. Our motivation started with wood framed construction since 94% of new build houses in the United States are made of wood. We additionally looked at CMU (Concrete Masonry Units) but not ICF. So, it's not a question we've answered.

Q: Have you considered various wall infill patterns or materials, for example, web versus solid, aerated concrete versus foam?

A: That's a great question for the structural people in my company. I've been there a year on the material side, so I don't have much input on print paths. However, many homes at Wolf Ranch have what you call a three-bead wall— a one bead exterior shell with a double-layer exterior shell. This isn't in the white paper because the current wall design is more efficient, the extra layer didn't add much structurally. We demonstrated that for our wall design, that extra layer wasn't needed. So, yes, design can lead to material efficiency gains, but I'm not sure about the infill patterns specifically. It's an opportunity for investigation.

Q: Has the public perception that wood is more sustainable than concrete impacted your ability to sell houses?

A: That's a question for the entire concrete industry. You shouldn't make a skyscraper out of wood so concrete will not compete with wood in all uses. But for residential and low-rise construction the green building message is often associated with wood rather than concrete. Wood has been more successful in promoting its perception of being sustainable, though they leave out the environmental impact on the ecosystem of harvesting trees. Life cycle analyses have shown the environmental cost of wood, but that's not the message they're leading with. Concrete is more transparent on their environmental impacts. Concrete can compete on sustainability, particular on aspects of resilience and operational (heating and cooling) advantages but concrete has some work to do on sustainable messaging.

Q: Besides embodied carbon, what are the most important metrics to track when it comes to 3DCP sustainability?

A: You would extend that to greenhouse gases, not just CO_2. At this point, when comparing the two homes, they perform the same; there isn't a special design that makes 3DCP better in terms of water or similar metrics. So far, it's a narrow focus on greenhouse gas and carbon questions. However, in the broader context, there are always opportunities to improve, and you hope the impact can be shown to be comparable or better.

Q: Do you expect that more sustainable construction would lead to higher monetary costs? How could consumers be incentivized to purchase 3DCP homes if this is the case?

A: Good question. If we dig into the literature which has numerous examples of one component binders (only cement) and low aggregate to binder ratios (often 1:1) the answer might be no — it can actually be cheaper to be more sustainable. Replacing cement with cheaper materials like sand, fly ash, or silica fume in the mix can reduce both carbon and cost. Each of our last three mix designs that we've developed and used industrially have gone down in both carbon and price. This is an opportunity for the industry to achieve both sustainability and cost efficiency.

Q: Does Icon or any of the literature sources you cited account for carbon sequestration through carbonation?

A: Yes, in the presented slide on embodied carbon, there was a part of the stacked bar chart that represented a carbon reduction associated with the absorption of CO_2 over the structure lifetime. This made a difference in the analysis. Without including this, the 3D printed wall would have a higher carbon footprint. The industry has accepted methods to account for this, and we do include it.

Q: Did the rounded corners contribute in any significant way to heating or cooling efficiency?

A: Unclear but it could be an area to study.

Q: Did you account for waste materials in your LCA calculations?

A: The Tally software handled the LCA. Waste factors are embedded for the A1 calculations.

Q: Did you account for embodied carbon in reinforced bars?

A: Yes, that's part of the Revit (BIM) plus Tally (LCA) process. Revit determines the quantity of reinforcing bars (and the mass of steel) that are in the walls, and Tally multiplies that mass by the steel emission factor, providing a complete carbon impact calculation for the house. All the materials are quantified this way: concrete, steel, glass, insulation, roofing, etc.

Q: Are you considering the OPC to be Type 1 or Type 1L for carbon calculations?

A: For the data I showed about the literature review, which is unpublished, I assumed an example of using the same Type 1L cement for every mix design. That comes with a specific CO_2 emission factor.

Q: Is there any concern about how the public's perception of 3DCP might change if it eliminates the need for certain trade jobs?

A: Interesting question. From Icon's perspective, it can be difficult to find people for many construction and trades jobs. So, if 3DCP allows us to use the existing workforce more efficiently, then it can help meet future construction needs without eliminating jobs—it just makes better use of the available workforce.

Q: Can we argue that 3D printed homes are more resilient to natural hazards like tornadoes or hurricanes and therefore more sustainable, as they won't need to be replaced as often as wood constructions?

A: That's something considered in our analysis with MIT, which aligns with the value proposition of concrete being more resilient than alternatives. Concrete buildings tend to withstand natural disasters better than wood structures. This thinking motivated us to work with MIT, but it didn't make it into the white paper due to time constraints. However, it was part of our analysis, and it supports the idea that concrete is more sustainable due to its resiliency.

13.9. Appendix G: Safety, Equipment, Workforce and 3D Printing Procedure Q&A

Q: Can you please elaborate more on the field sampling procedure at the nozzle? For example, if we are sampling at the nozzle during a print of a large element (say a large bridge girder), this could potentially induce some "cold" joints. How would you balance the field sampling procedures vs. potentially inducing weak points in an element?

A: You can't send the material dry to the nozzle, so you can't reduce your water at the mixing process to make up for it at the end and have enough time to hydrate the material properly. Once the material is mixed, anything you do to it afterward changes its characteristics. Adding liquid at the end decreases your strength. Sometimes it's not that bad, depending on what you're doing, but you have to remember, when adding color, you're only adding 0-6%. Anything above that is a waste—you're not changing the color any further. It reaches its maximum effectiveness. The machine is built to add liquid color at the nozzle, but we found that the strengths drop off so much that we refuse to do it. So, we add powder at the back. It's easier to add a little bit back at the pump than to try and add the liquid to the nozzle. I deal a lot in the labs, so I spend time in Aurora, where I help design the machine that dispenses the powder.

Q: For small applications like the house columns you show, do you think 3DCP was the best/most practical option, or is it just the novelty that makes it appealing? Do you think applications like this will be a significant part of printing in the future, or will it mainly be larger structures like homes and infrastructure?

A: Was it practical? Absolutely not. They were trying to prove that it could be done. That's the only reason. It was a newer idea. Why would it be pink? They used this really bright salmon color. They didn't need to do that for a parking garage. They could have done 100 different things, but they were trying to show that VE can be structural and used in that application. If we don't reach out and try, we're never going to make it grow. The labor force is the worst part of it—many in the labor force are aging out, and there aren't enough young people to replace them.

As for the future, it will be a part of it because there is no workforce. The skilled labor that we had—the masons, structural engineers, and others who did this work daily—they're not there anymore.

Q: What have European countries done differently that they've developed standards faster?

A: They're three years ahead of us. They started long before we did and took it seriously, making it a priority in their countries. Switzerland started, and we could talk about companies like Putzmeister, which started their process of making equipment 16 years ago. I remember the machine when it first started. They've had 3D in their minds for a longer time than we have, and that gives them the advantage. Does it mean they're better? That's the trick.

Q: For the regions you mentioned having adopted 3D printing into building codes (e.g., Brazil), are there any lessons you think could apply to U.S. codes?

A: Some, but I can't be specific because I don't deal with their codes that much. I just help them get up and running. I know they're all working on it, and many are following the European code. In the U.S., it seems like we just want to do our own thing, rather than making it uniform across the world.

Q: German specs—how different are their specs?

A: I don't have a clue. I didn't build it myself. I was there while they were building, but I didn't get involved in that. That's way above me.

Q: For exterior walls, how do you prevent water penetration but still have good vapor permeability to avoid condensation, especially in between the walls?

A: It depends on the products. There are so many different products for sealing. How much air is entrapped in your material? My material's density is very high, and air entrapment is low, but that's our material, not everyone's. Some stuccos and other materials used for insulation or sealing don't bond to the material underneath. You must remove any curing agent before applying a sealer or bonding unit.

Q: What is the curing procedure for the 24-hour cubes?

A: It depends on your material. Most people take standard cubes, put them in water, and break them the next day. We don't do that. Our material doesn't even need a curing agent. If it's really sunny, you can wet it down if you like, but the material is designed not to crack, so there's no need for a curing agent. If it's that bad, don't print that day.

Q: Does your brand have any kind of standards to begin with?

A: We have our own standards that we follow in the lab. Sika has its own testing format for any materials we work with. We run materials through a series of processes, well beyond what any of the specs would require, and we don't just do it once. Everything done in the lab is tested at least 15 times before it's even considered for field trials.

Q: Can you touch on the challenges of locally sourcing raw materials for your formulations?

A: That's fun, yeah. Local materials are always difficult. We manufacture in three locations to ensure consistency—dry sands, materials to spec, aggregates, and sands all to a certain size. Using local sands and cements was an issue in the past, but Europe has already done it, and now we're doing it with our own added packages. Every location is different, so each location has to be tested separately. If I'm doing a project in Maryland, I need local sands and cements, and then I can calibrate the formulation. The challenge is huge.

Q: You mentioned the 24-hour curing and transit testing. Can you elaborate on that?

A: I take a compression machine to the site for breaking blocks, even on the roof if it's a big project. The key is to be there and show them the correct process. Any of these projects, they like to bring a chemical engineer or an R&D technician on-site, which is good in some ways but bad in others. They might think the material should perform one way, but it has to do something else. Sometimes they wind up doing what they want instead of what's required.

Q: Do any of your customers ask about sustainability or EPDs?

A: Absolutely. Sustainability is the biggest concern. For example, our housing material uses 65% less cement. Some customers care about that, especially when you present it in the market. Sustainability is important, but it's challenging because what you save in materials, you might spend on transportation. The diesel trucks that transport materials don't care about the environment. We've invested a lot in making our plants more sustainable, but we can only do so much because of the costs involved.

Q: Can you please elaborate more on the field sampling procedure at the nozzle? For example, if we are sampling at the nozzle during a print of a large element, say, a large bridge girder, this could potentially induce some cold joints. How would you balance the field sampling procedure versus potentially inducing weak points?

A: I never interrupt the print. You should take your samples at the very beginning, once you know you've got the consistency right and the material is flowing correctly. Fill your blocks at the start. When you stop the print, take another sample. When you clean out the nozzle before finishing, take another sample. Taking it out of the hopper doesn't help—you can't interfere with the print. Sometimes people think they can print all the walls at once, but that's not practical. With the right equipment, you can print a large section, but it's not usually done in one go. The workforce isn't trained for it. On some jobs, the material isn't managed properly, and that causes issues. You have to be vigilant and ready to address problems as they arise.

13.10. Appendix H: Canadian Standards Development

Q: How do you model the layer interfaces in FEA?

A: We make sure the mesh matches the layer height. For example, we typically print with 40-millimeter-tall layers, so we make the meshes a multiple of 40 to get the intersection there. To connect those elements, we use a cohesive material model. Basically, we have a kind of virtual link between the nodes. There are two nodes at the same coordinate, and we use this virtual link to connect them. Once we achieve the tensile strength determined through testing, the connection fractures, and those nodes are now disconnected. It's similar to modeling discrete cracks in software like Abaqus or Atena. That's the approach we take for the interlayer bond.

Q: How were the parameters of the cohesive zone for the numerical model obtained? Can you talk more about the material cards, type of material, and modeling platforms used for the FE model?

A: Right now, we're using Abaqus. The images I showed were extracted from Abaqus. In terms of material, it depends because we deal with more than one type of material. Usually, we characterize the material when printing large-scale specimens. For example, if I have three large-scale specimens, I print an extra one just to cut cubes and perform four-point bending and compressive cube tests based on the mortar ASTM standards. We use those standard tests to determine variables. The constitutive model is straightforward—linear up to the tensile strength, and then it's gone. The geometry modeling is tricky because making the mesh match the printing layers is the most challenging part for us.

Q: How do you see 3D printing supporting virtual inspection?

A: I might have misunderstood the question. Are you referring to a slide from the CDSP program? If so, that's probably from the NRC package. We are part of that group, and it's a bit outside our 3DCP scope. The virtual inspection mentioned is part of the NRC package, where we're just being the messenger here. Sorry for the confusion; it's not directly related to our 3DCP work.

Q: What software have you found to be the best for FEA for 3DCP?

A: We haven't tested many, but Abaqus has been the best for us because it's very flexible when it comes to geometry. So far, Abaqus is the only one we've tried.

Q: What standard do you use for your four-point beam test?

A: We use the same standard as for concrete. It's the ASTM four-point bending standard (ASTM C78), also known as the third-point bending.

Q: What about standard development related to durable properties, permeability, and chloride penetration?

A: We've done some tests on permeability, and the research paper is still being written and reviewed. Regarding standards, I'm not sure if there's anything specific on the ASTM side about permeability in the four groups, we're part of. Durability isn't fully covered yet, but it might just be a matter of group creation. There are groups working on permeability and durability tests, and within the next year, we might see publications that could lead to standards development.

Q: For the wall prisms, even without the webbing, did these specimens have the same cross-sectional area?

A: No, they didn't. You can see from the force values that the load is not the same. The two printed prisms have similar areas, but the CMU (Concrete Masonry Unit) had a bit more area. That's why we compare the strength in terms of stress (MPa), not load, because the cross-sectional areas are different. Although that was my actual response, I later reviewed the areas and found they are very similar, which was intentional.

13.11. Appendix I: Exploring 3D Printed Real-Estate Perspectives: Opportunities and Challenges Q&A

Q: How about having a third party, like academia, collect honest opinions from residents living in a 3D printed house, including pros and cons? Some residents may have lived there for a couple of years.

A: Yes. That is exactly what we need. Some of my colleagues in construction science and architecture are already working on this—focusing on livability and comfort. They're looking at how occupants feel about room finishes, colors, temperature, lighting, and more. They use sophisticated equipment to measure these aspects and study human behavior. This research also involves sociology. One of the big questions that came up was about the lines on the walls. It may seem silly, but some folks are scared of the lines. We need to overcome this. We are planning to do some research on this topic, and we would love to connect with residents who are experiencing these homes daily. If it's something that people get used to after a few days or weeks, like with any bold wallpaper pattern, then that's great, and we can put that concern to rest.

Q: Can you talk about residential low-rise construction in the next three to four years, especially regarding cost and the possibility of mixed-use 3D printing on exterior walls? Any trends in the market?

A: Because we are currently focusing on single-family homes, we haven't looked closely at mixed-use or multifamily units yet. However, to address the housing market's affordability issues, mixed-use developments are definitely trending in urban environments due to the lack of space and the need for more housing units. I see a lot of innovative technologies emerging, like SIP panels, and I think a 3D-printed panelized system would be a great entry into that market.

Q: Are you aware of any financing concerns related to 3D-printed homes?

A: At the moment, talking with developers, they haven't identified any financing problems for homeowners. The ability to get a mortgage is there as long as the home is properly valued. If you can get a good comparable valuation, you'll get a mortgage—someone will give you money. The problem doesn't seem to lie there. In terms of builder financing, there are some incentives to push this technology because it's an emerging field. We've seen some incentives for developers to advance this in the market.

Q: Where are the children of Gen Z, and how will these houses fit with their families? Any information on that?

A: The children of Gen Z—well, I consider myself a Gen Z person, though I'm technically on the cusp of Gen X. The question seems to be about the future, maybe 20 years from now. Gen Zs, who are now in their 20s, are the YouTube generation. The millennials, who are a bit older and in their 30s, have different perspectives. Many of them didn't buy into the concept of homeownership, they don't believe in the American dream of owning a home, and many are in debt, which causes frustration.

Looking ahead, I believe that retirement communities might be the perfect market for 3D-printed homes. Retirees have money to spend and might be more adventurous with their home choices. A 3D-printed home could be ideal for them because it's low maintenance, and they wouldn't need to change anything as they age. However, we don't yet have data on this market segment, but I think it's a strong entry point for these homes.

Q: Talking about trades, what issues do the photographs on the right side of your slide illustrate?

A: The main issue is that tradespeople can't be on-site when the printer is active. The unknowns are the biggest problem. Many solutions are adapted on the builder's side, such as how to handle cutouts and where the problems might arise. The builder devises the solution, but then there's a need to train electricians, plumbers, and other tradespeople to work with the system. This involves more in-house training and planning. It's not like traditional construction where everyone can work around each other; this requires more coordination and training, especially from the builder's side.

Q: There is a need for standardization. We want to see standardization on the inside because definitely, we don't want to have conflicts on the outside, right?

A: Yes, definitely. You wouldn't want your electrical wiring on the outside of your home. Black Buffalo and others are working on the electrical aspects, and there are different creative ways to approach this. Standardization is essential, and it's something we're considering as we move forward.

Q: Any comments on the Fannie Mae guide to selling homes incorporating 3D-printed homes?

A: I'm not sure if everyone is aware, but Fannie Mae has provided guidance on selling 3D-printed homes. It's relatively new, and insurance companies like State Farm are also getting involved. This is helping to push the industry forward. I don't have specific comments, but it's something worth noting as the market continues to develop.

13.13. Appendix J: Breakout Session 3: Standards Impact on Finance, Real Estate Development, Research Development, Commerce, Labor, and Safety.

The following is the detailed export from the digital collaboration platform (ranked by attendees as to their level of importance or impact on the topic).

Real Estate Development & Financing Impacts
Positive Impacts: • Lender confidence increased as standards enable multiple structures and comparables for assessment (10)   • Insurance underwriter confidence that a structure has undergone some standard quality control (9)   • Diminish risk for financial institutions and insurance (5)   • Reduces community barriers that allow for faster/easier developments to progress from concept to breaking ground (4)   • Standards help create baseline quality (4)   • Better financing options can grow the market, mainstreaming 3D construction buildings (4)   • Faster Construction - Standardized processes can lead to quicker project completion (3)   • Increased resiliency should allow for better financing options (3)   • Could help gain access to grant money from localities (2)   • Protecting the public (2)   • Standardize pricing (2)   • Standards can help to make engineers more comfortable with adoption, resulting in developers gaining access to earlier financing (2)   • Buyers & financiers feel more confident (2)   • Buyer confidence that a structure has been built to code (2)   • Assurance of consistency (1)   • Building code facilitates permitting (1)   • Lender confidence based on build quality (1)   • Lower Maintenance Costs - Durable, standardized materials can reduce long-term maintenance (0)

- Design Flexibility - Encourages innovative design approaches, potentially increasing property value (0)

Negative Impacts & Potential Solutions:

- Restrictive codes could prolong permitting (7)
  - **Potential Solution:**
    - Performance-based wall system with well-explained pre-qualification standards/regulations. [Score: 100%]
- Could result in higher cost (4)
- Learning Curve - Developers may face a steep learning curve in understanding and implementing standards (3)
  - **Potential Solution:**
    - Ensure code language is stable enough to be adapted and updated by the policy folks in a way that won't scare off developers. [Score: 100%]
- Limits design creativity (3)
  - **Potential Solution:**
    - Make language as flexible as possible (e.g. through accepting performance as well as prescriptive standards). [Score: 100%]
- Could make things more challenging from compliance (2)
- Could become restrictive, flexibility, HOA requirements (1)
- Development of a certification program [Score: 76%]
- Standard may restrict architectural design variability (13)
  - **Potential Solution:**
    - Architects and designers engage in the standardization to prevent restrictions to architectural design [Score: 83%]
    - Restrict standards and regulations to structural aspects [Score: 71%]
    - Enable versatile design through approval of sub-assemblies [Score: 59%]
    - Enable clear ways to get a new geometry pre-qualified [Score: 79%]
- Standards may increase material costs (7)
  - **Potential Solution:**
  - Current state of overdesign could see cost decreases as standards reduce overdesign [Score: 69%]

    - Encourage the development of performance-based costs and standards and ensure the producer has flexibility [Score: 81%]
- Standards may discourage builders from using the technique if not familiar (5)
    - **Potential Solution:**
        - Industry group subsidizes the costs of standards to increase diffusion of knowledge [Score: 63%]
        - Introductory price breaks to get standards into the hands of early adopters [Score: 43%]
        - Make standards available to everybody to increase familiarity and reduce doubt [Score: 65%]
- Variable requirements with different AHJ's (0)

Research Development Impacts

Positive Impacts:

- Promotes collaboration between industry, academia, and government agencies (10)
- Can enable alignment of R&D efforts across the industry, people using the same metrics will help build more usable literature, a stronger knowledge base, to move faster on codes and standards (6)
- Catalyze more research because the state of the art and new avenues of exploration are easier to identify (4)
- Standards can generate faster and more reliable results, offering more accuracy of results, building confidence and enabling broader adoption (4)
- Kicks off a feedback loop of R&D for better and better standards (3)
- Standards will increase TRL, naturally increasing interest (3)
- Easier to compare field results (2)
- R&D will guide us to confirm if current durability standards are in line with 3D Printing (1)
- RD allows innovation and new Potential Solutions that are performance-based and not prescriptive (1)
- Research community develops standards, so it's work for them (0)

Negative Impacts & Potential Solutions

- Could artificially constrain research to fit within guide rails (11)
    - **Potential Solution:**

        - Ensure collaboration between industry and research to ensure that research is informing codes and standards. [Score: 80%]

- Research often outpaces standards (7)
    - **Potential Solution:**
        - Ensure collaboration between industry and research to ensure that research is informing codes and standards. [Score: 80%]
- 12 - Once in place, standards can be difficult or slow to change, need to get it right up front. Also need everyone to adopt them for it to work, buy in (8)
    - **Potential Solution:**
        - #12 Must make sure you have good representation in codes and standards issuing body and collaboration across industry, academia, and govt [Score: 92%]
        - #12 Though difficult, potentially shorten revision cycle times given the newness of 3DPC [Score: 81%]
- 17 - Standards often require special and expensive equipment that everyone may not have access to (5)
    - **Potential Solution:**
        - #17 Standards must be practical, not cost prohibitive. Good participation will help prevent this [Score: 76%]
- 57 - Current practice may impede technological advancement (0)

Workforce/Labor Impacts

Positive Impacts:

- Can alleviate labor shortages (6)
- Standards can enable other trades to work within 3D construction homes easier, right now they are not sure how (5)
- Can improve skill set of willing labor (5)
- Training on-site improves QC of product (4)
- Enables standard training that promotes worker mobility between employers (4)
- Incentivizes new generations that are into technology to enter the construction industry (3)
- Can extend the longevity of the workforce, less physically intensive labor (3)
- New jobs (transferability of skills, skilled labor) (1)
- Job Creation - Standards can lead to the creation of new roles in tech and quality control (1)

- Skill Enhancement - New standards may require upskilling, leading to better-trained workers (1)
- Standards can lead to the right training for jobsite PPE (1)
- Catalyzes labor force into a true trade (1)
- Dovetailing with positive workplace safety impacts, it encourages more new workers (0)
- Education of new labor force (0)

Negative Impacts & Potential Solutions

- Training Costs - Significant investment in training programs for workers to adapt to new standards (7)
    - **Potential Solutions:**
        - Standardized training programs can help lower cost. [Score: 51%]
        - Trade school partnerships. [Score: 100%]
        - Develop industry-wide training programs through associations or consortiums, pooling resources from multiple companies. This collective approach can lower per-company costs and standardize the training process. [Score: 71%]
        - University partnership for curriculum development. [Score: 100%]
        - Utilize labor union partnership to leverage available funding for training. [Score: 100%]
- Could be an issue if it's not machine agnostic (5)
    - **Potential Solutions:**
        - Create general training programs associated with standards in several categories that can be applied across machine and material types. [Score: 100%]
        - Develop and adopt open standards for 3D concrete printing that are not tied to any specific manufacturer or technology. These standards should define the essential processes, materials, and quality requirements that all machines must meet, regardless of the brand. [Score: 100%]
- Lost jobs through automation (0)
    - **Potential Solution:**
        - Standards should help to increase job availability in the industry. [Score: 51%]
- Print speeds decreased due to workplace limits on worker proximity to moving equipment (8)

- **Potential Solution:**
  - Use remote sensing to track worker movements near printer or to let workers perform tasks remotely [Score: 54%]
- Resistance to learning/increasing skill gaps (6)
  - **Potential Solution:**
    - Incentivize learning initiatives and highlight growing demand for specialized skills [Score: 78%]
- Workforce may be decreased as standards replace the need for extra people (5)
  - **Potential Solution:**
    - At odds with current labor shortage, offer retraining initiatives [Score: 63%]
- May lead to job displacement either in removing current positions or teaching skills that are only applicable in a niche (4)
- Differences in skill sets needed for a regular construction job vs a 3DPC job might prevent companies from investing in more labor (2)
- Changing regulations may outpace learning and teaching (2)
- Economic inequality can act as a barrier to learning new skills; standards forcing training could increase this inequality without proper incentives (1)

Safety Impacts

***Positive Impacts*:**

- Safety is paramount, standards for operation and structural considerations can prevent injury and death. A 3D construction-related injury or death would be an enormous setback for the industry (7)
- Standards could reduce overly conservative designs to appropriately conservative designs (6)
- Can promote a safe working environment with certification of operators (6)
- Enhanced Safety Protocols - Standards can incorporate advanced safety measures, reducing on-site accidents (4)
- Can dictate proper disposal of waste material (4)
- Encourage site-specific geometry to reduce hazards and increase accessibility (4)
- Safety of building occupants (3)
- Could improve labor safety (2)
- Can promote a safe working environment with certification of operators (2)
- This method of construction can reduce the jobsite safety accidents during printing (1)

- Safety of a printed structure can be improved if following all the standards (variability can be reduced, once standards are developed) (1)
- Necessary for safety standards - labor (0)
- Could help weed out bad actors (0)
- Improvements to safety of structure (0)

Negative Impacts & Potential Solutions

- Safety standards can produce a false sense of security (7)
    - **Potential Solution:**
        - Articulate the scope of what any safety-related standards endeavor to cover (and what they don't). E.g. job site safety vs long-term safety of building structure. Make sure that standards collectively are thorough enough not to leave any scope gaps. [Score: 100%]
- Could be used as an excuse to not use common sense (6)
    - **Potential Solution:**
        - Make sure standards are simple enough to be followed and to be enforced. They should be written to the level of the audience they're intended to address (e.g. researchers vs installers). [Score: 100%]
- Consistency of end product can be improved (0)
- Time for training could lead to (0)
- In terms of design safety, additional safety features could lead to overdesign, excess utilization of material, costs (9)
    - **Potential Solutions:**
        - More R&D would lead to lower future costs [Score: 87%]
        - Create design requirements as per regional needs [Score: 83%]
        - More R&D reduces uncertainty which reduces need for over-conservatism thus saving material and cost [Score: 78%]
        - Balance standard conservatism with end use and environmental exposure (e.g. seismic requires more conservatism until well understood) [Score: 57%]
        - Design conservatism should be proportional to criticality of structure being designed [Score: 74%]
- Time required for training would increase initial costs (5)
    - **Potential Solutions:**
        - Create project thresholds that trigger the need for training and certification [Score: 77%]

- Create levels of training for project-specific requirements where operator competency is more important (refer to welding and shotcrete certifications) [Score: 64%

3D Printing Procedures Impacts

Positive Impacts

- Could reduce building permit time and planned review (6)
- Can improve sustainability by reducing the waste material (5)
- Allows new companies to quickly enter into this industry (4)
- Improvement to QA/QC (3)
- Allows for safety standard procedures across industry (3)
- Allows the builder to keep detailed records during printing (2)
- Facilitates after-print modifications by trades (1)
- Consistent results (1)
- If there is a procedure recommendation that could mitigate potential litigation (1)
- The technology allows for high precision and the ability to create complex, customized designs that would be difficult or impossible with traditional methods (0)

Negative Impacts & Potential Solutions

- Could stifle innovation in materials (6)
    - **Potential Solution:**
        - Make standards flexible enough to accommodate innovation. E.g. through a prescriptive pathway and a performance-based pathway. [Score: 100%]
- Stymies innovation (5)
    - **Potential Solution:**
        - Make standards flexible enough to accommodate innovation. E.g. through a prescriptive pathway and a performance-based pathway. [Score: 100%]
- Recommendations for field procedures could be limiting (1)
    - **Potential Solution:**
        - Make standards flexible enough to accommodate innovation. E.g. through a prescriptive pathway and a performance-based pathway. [Score: 100%]

- Standards could impact innovation (9)
    - **Potential Solutions:**
        - Standards should include a section or chapter on performance-based testing to allow innovations to prove equivalency to the standard [Score: 81%]
        - Limit the scope of the standard and supplement with guidelines [Score: 61%]
        - The consortium could develop initial standards allowing innovation, though changes in construction industry standards take time [Score: 85%]
        - Standard should only include critical safety requirements [Score: 62%]
- Existing standards could increase cost, or slow innovative new procedures from being adopted if they were to come after standards are already in place (7)
- Standards should not govern jobsite means and methods (2)
- Different procedures for different printing systems => potential for confusion within industry (2)