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Automated Construction of Expeditionary Structures (ACES)

Materials and Testing

Ghassan K. Al-Chaar, Peter B. Stynoski, Eric Kreiger, Todd S. Rushing, Lynette A. Barna, Jedadiah F. Burroughs, and Michael P. Case

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Abstract

Complex military operations often result in U.S. forces remaining at deployed locations for long periods. In such cases, more sustainable facilities are required to better accommodate and protect forward-deployed forces. Current efforts to develop safer, more sustainable operating facilities for contingency bases involve construction activities that require a redesign of the types and characteristics of the structures constructed, that reduce the resources required to build, and that decrease the resources needed to operate and maintain the completed facilities. The Automated Construction of Expeditionary Structures (ACES) project was undertaken to develop the capability to "print" custom-designed expeditionary structures on demand, in the field, using locally available materials with the minimum number of personnel. This work investigated large-scale automated "additive construction" (i.e., 3D printing with concrete) for construction applications. This report, which documents ACES materials and testing, is one of four technical reports, each of which details a major area of the ACES research project, its research processes, and its associated results. There major areas include System Requirements, Construction, and Performance; Energy and Modeling; Materials and Testing; Architectural and Structural Analysis.

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Preface

This study was conducted for the Assistant Secretary of the Army for Acquisition, Logistics, and Technology (ASA(ALT)) under Programs: 622784T41, “Military Facilities Engineering Guidance,” 622784T45, “Energy Technology Application Military Facility Guidance, and 633728002, “Environmental Compliance Technology Guidance”; Business Area: “Environmental Quality – Installations”; Thrust Area: “Infrastructure for Combat Operations”; Work Package: “Automated Construction of Expeditionary Structures.” The technical monitor was Kurt Kinnevan, CEERD-CZT.

The work was performed by the Energy Branch, of the Facilities Division, U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication, Mr. Jedediah Alvey was Acting Chief of the Energy Branch; Ms. Michelle Hanson was Chief of the Facilities Division; and Mr. Kurt Kinnevan was the Technical Director for Installations. The Deputy Director of ERDC-CERL was Ms. Michelle Hanson and the Acting Director was Dr. Kirankumar V. Topudurti.

COL Teresa A. Schlosser was Commander of ERDC, and Dr. David W. Pittman was the Director.

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1 Introduction

1.1 Background

1.1.1 The expeditionary paradigm

After the "Cold War," the need for forward positioned CONUS-type installation facilities disappeared and a new dynamic evolved. The Armed Forces needed to become expeditionary in nature. U.S. Forces needed the capability to deploy to any location and establish the means to conduct joint military operations, to successfully conduct those operations, and then to retrograde back to their "home station." The U.S. Army is currently in the midst of a paradigm shift characterized by the ability to project its military power abroad from a CONUS base in an expeditionary manner. The changes from how Cold War operations were conducted, and how future missions are being conducted, are significant. However, there is one common thread between them, the need to be able to "encamp" a military unit at any location on the earth with requisite operational support capabilities (EO-OIF 2008).

Since 1989, the United States has engaged in numerous military operations across the Middle East, Central Asia, Africa, Europe, South America, the Pacific Basin, and the Caribbean. For the foreseeable future, U.S. forces will likely continue to operate in a global environment of persistent conflict, characterized by protracted confrontation among numerous actors who use violence to achieve political and ideological desired end states. Military operations will involve the commitment of U.S. forces to operations in environments characterized by complex rural and urban terrain, lack of front lines, insecure flanks, dismounted combat, and constantly-fluctuating situations. Many operations will take place over large areas in austere and demanding environments, making the safety of those lines of communications and force protection for the associated logistics units an operational imperative for the commander.

To contend with the uncertainty and the many security challenges of the expeditionary condition, the U.S. military will require bases and stations within and beyond Western Europe and Northeast Asia, and temporary access arrangements for the long-distance deployment of U.S. forces (Bush 2002). Protecting the United States also requires the integration of military capabilities with other government and law enforcement agencies to manage the consequences of an attack or natural disaster (NMS 2011). As the Army transforms to meet these needs, the power projection platforms from which the Army operates will also need to transform in a number of ways:

- Deployed forces will need to evolve into more self-sufficient organizations.
- Base camp footprints will need to shrink correspondingly.
- The resources needed to construct and maintain bases will need to migrate from imported materials to ubiquitous, locally recognized and used materials.
- Construction requirements for materials, personnel, and time to construct will need to decrease.
- Constructed structures will need to be more modular, scalable, adaptable, supportable by local infrastructure, and more energy efficient, and survivable.

In many instances, the need to conduct complex operations results in U.S. forces remaining in these locations far longer than initially anticipated. Consequently, more sustainable facilities are required to better accommodate and protect the many forward deployed forces who remain for extended periods. The changing threat posture in these locations also introduces the requirement that facilities be designed to include improved force protection measures. These evolving facility needs and requirements across basecamp functions dramatically increase the demand for resources. Basecamp commanders and mayors frequently have to make difficult decisions on how to best prioritize efforts using the limited resources available in the harsh and austere environments of the deployed locations.

The U.S. Army conducted a Capabilities Based Assessment (CBA) on Base Camps from 2009 to 2011 and presented the results to the other Services at a conference in May 2011. The CBA identified 195 gaps and analyzed 120 for solutions. At the conclusion of the conference, the representatives from the U.S. Air Force, U.S. Navy, and U.S. Marine Corps endorsed the CBA and its findings as Joint capability requirements.

The key operational outcome of the CBA effort on contingency bases was to provide the Joint Forces, operating in a Joint, Interagency, Intergovernmental, and Multinational (JIIM) environment at all levels, contingency locations that can enable force projection and application (TRADOC 2009). To provide this physical location for force application, the Joint

Force will require capabilities to construct and operate contingency locations in the most effective and efficient manner. Likewise, these capabilities must support the operational mission in the most effective, efficient, and sustainable manner. They also must be approached in a manner that capitalizes on their interdependence in order to provide the combatant commander the following force multiplying effects:

- Reduced threat opportunities for attacks due to smaller logistics footprints while still supporting the same level of operational capabilities and readiness.
- Increased flexibility in base operations support through improved standardized designs that are modular, scalable, adaptable, and interoperable between the Services.
- Decreased construction and deconstruction requirements (time, material, equipment, manpower).
- Improved operations management (power, water, and waste) that reduce military, civilian, or contractor oversight and support.
- Improved design of major utility backbones that support operational agility because they are designed for maximum occupancy and duration, or are extensible as plans change.
- Improved safety and occupational health elements for all aspects of contingency location life-cycle to prevent and minimize casualties, damage to property, and minimize risks of acute or chronic illness or disabilities.
- Improved security and protection (including chemical, biological, radiological, and nuclear [CBRN]) that reduces diversion of manpower and other resources from operational missions.

Recent contingency operations have shown that vulnerabilities to U.S. forces occur at our bases both “inside the wire” and during logistics supply activities “outside the wire.” To mitigate these vulnerabilities, efforts are underway to develop safer and more sustainable operating conditions for contingency bases, as evidenced by the capabilities-based assessments completed by the U.S. Army Training and Doctrine Command (TRADOC) and other service organizations. Key elements of these efforts involve construction activities, more specifically: (1) the associated resources (material, personnel, and equipment) to build, (2) the types and characteristics of the structures constructed, and (3) the resources necessary to operate and maintain the facilities once construction is complete.

1.1.2 Automated Construction of Expeditionary Structures (ACES)

Construction actions require significant resources during contingency operations in the form of materials, equipment, personnel, and facilities for transport, logistics management, and security operations. The current construction process is labor intensive. Many of the processes common in the construction industry are similar in type and complexity to those in a number of manufacturing industries. However, where the manufacturing sector has been transformed with the use of robotics and automated systems, the construction industry has not. Some technologies used in manufacturing offer viable options for many types of construction, even when they have high weight and large volume requirements.

Additive manufacturing ("3D-Printing") is the industry method for creating parts from computer designs through a layered deposition process. Additive construction is a fabrication technology that uses computer control to exploit the surface-forming capability of troweling to create smooth and accurate planar and free-form surfaces out of extruded materials at a construction scale. This research intended to develop and evaluate the capability to perform construction using an automated, additive process using locally available materials.

At the beginning of the ACES program, there were no funded research and development programs that would have provided an additive construction capability in a form that would be employable by the U.S. Army within the next 10 years. Without the investment by the Army and the National Aeronautics and Space Administration (NASA), a deployable automated construction capability would have been unlikely to become available for 15 – 20 years, as initial efforts employed massive fixed-plant component-based approaches. With the creation of a Cooperative Research and Development Agreement (CRADA) with Caterpillar, Inc., ERDC and NASA occupied a unique, first-to-market niche in development of a mobile and deployable automated construction capability.

The requirement for this research was staffed through the U.S. Army Maneuver Support Center of Excellence (MSCoE) using a formal review process, resulting in their full endorsement. In addition the product manager for Combat Engineer and Material Handling Systems (PdM CE/MHS) has been engaged and concurred that a successful research effort would appropriate to transition to a configuration such as an Engineer Mission Module mounted on a flatrack that can be hauled by the Army's Palletized Load

System (PLS) vehicle. The Army Facility Component System (AFCS) B-Hut was used as the baseline for footprint, envelope volume, construction requirements, and sustainment requirements.

This research resulted in a system that requires fewer personnel and material resources for construction, security, logistics support, and operations. As the construction process becomes automated, fewer personnel will be required to build the structures and to maintain security and sustainment during and after construction. Likewise, using local materials for the automated process will require less material to be shipped into the area of operations; thus, fewer personnel will be needed to provide transportation and security of these materials as well as fewer personnel to manage the construction materials during transit and storage on site.

Automated (additive) construction of structures also improved energy efficiencies over current designs, increased durability, and provided more adaptability while at the same time requiring less resources and fewer personnel to sustain. Since local materials are the primary source for construction material, the availability and time-to-use of the material will also be greatly reduced. Figure 1-1 summarizes the advantages of ACES over convention construction.

Ancillary benefits of using local materials include, (1) structures can be built in a way that may be more acceptable for subsequent use by the host population, (2) can be designed to match existing architecture appearances and aesthetic values, (3) maintenance and repair materials are readily available, and (4) their uses are understood by the local population. In addition, robotic construction would permit automated application of camouflage, concealment, and deception strategies to structures as they are constructed.

Figure 1-1. Conventional construction vs. ACES construction.

Conventional Method vs. ACES

	Conventional	ACES
Construction Time	4 – 5 Days per structure	< 3 Days per structure
Soldier/Contractor	8 personnel per structure	3 personnel per structure
Manpower Intensive	8,000 man-hours	4,000 man-hours
Materials Shipped	5 tons	< 2.5 tons
Construction Waste	1 ton	Minimal
Improve Energy Efficiency	R2 or less	R15 – R30

Other objectives for ACES:

- Understand how to use readily-available onsite materials (i.e., cement, concrete)
- Understand performance characteristics of printed structures (structural, protection)
- Explore ability to print different types of structures

The Automated Construction of Expeditionary Structures (ACES) project was undertaken to develop the capability to “print” custom-designed expeditionary structures on demand, in the field, using locally available materials with the minimum number of personnel. The 3-year ACES research project is documented in four separate technical reports, each of which details a major area of research processes and associated results, including:

- System Requirements, Construction, and Performance
- Energy and Modeling
- Materials and Testing
- Architectural and Structural Analysis.

ACES research has successfully developed a system that incorporates all the key elements for safer, more sustainable contingency base facilities: (1) a capability to rapidly construct structures using less and fewer resources (material, personnel, energy, etc.), (2) the capacity to provide improved force protection measures, and (3) a requirement for fewer resources to operate and maintain the completed facilities. Once fully implemented, this system will help basecamp commanders and mayors resolve work priorities by reducing the demand on limited resources available in severe deployed environments. ACES will enhance power projection capabilities by improving the effectiveness, efficiency, and sustainability of U.S. forces and their basecamps.

1.2 Objective

The overall objective of this research program was to develop a technology that has the capability to construct ("print") custom-designed expeditionary structures on-demand, in the field, using locally available materials, with a minimum number of personnel.

The intent was to develop a construction capability that will reduce construction time, personnel (construction, operations and maintenance, and sustainment/logistics), and materiel necessary for construction. The research sought to use existing military transportation platforms on which to mount the technology. The Army Facilities Component System (AFCS) B-Hut will be used as the baseline for footprint, envelope volume, construction requirements, and sustainment requirements.

Specific metrics for the objectives of this effort included the need to:

- reduce construction time from 4 to 5 days to 1 day per structure
- reduce Soldier/Contractor requirements for construction from eight personnel to three personnel per structure
- reduce logistics impacts associated with materials, personnel, and resources to sustain the structures and personnel
- decrease material shipped from out of theater from 5 tons to less than 2.5 tons
- improve energy performance of the envelope from less than R1 to greater than R15
- reduce sustainment (logistics) and operations/maintenance personnel
- reduce construction waste from 1 ton to less than 500 lb
- improve security during construction
- improve local population acceptance by mimicking local construction.

1.3 Approach

1.3.1 Formulation of the team

This program brought together expertise from within ERDC, collaboration with the National Aeronautics and Space Administration's (NASA's) Marshall Space Flight Center (MSFC) and Kennedy Space Center (KSC), and the academic expertise from the University of Southern California (USC) to conduct highly focused research designed to prototype an automated construction system that can fabricate a ~500 sq ft structure in less than 24 hrs. The major areas / teams were:

- Materials Formulation and Testing Team
- Hardware and Controls (Building) Team
- Architecture / Design Team
- Integrated Systems Performance Testing Team
- Energy Performance (Modeling) Team
- Structural Analysis Performance (Modeling) and Test Team
- Overall Schedule Team
- NASA Support Team.

1.3.2 Early design efforts

The objectives of the early design efforts were accomplished by investigating concrete mixture designs and admixtures to adapt locally available cementitious materials to meet required rheology, curing time, and strength for use in an additive delivery process. These investigations are the focus of the present report.

The effort included the development of physics-based models and simulations to analyze various designs for structural strength, energy efficiency, logistics savings, and labor requirements, the results of which are to be packaged for future trade space visualization that could be employed by the Engineering Resilient Systems (ERS) work effort.

One of the critical efforts to meet these objectives will be the development of a sensor-based end-effector and material flow control system capable of producing required positional accuracy and stability to enable the mounting of lightweight deposition equipment on existing military equipment. This is critical not only because it enables the delivery of the construction material in a controlled manner, but also because it reduces the number of personnel necessary to support the construction process.

Finally, to empirically prove that the results of the objective have been met, a prototype system will be developed that is capable of constructing a B-Hut equivalent structure (~500 sq ft) in 24 hrs or less, including custom-designed structural beams, trusses, and vaults. These structures will then be evaluated for energy efficiency and durability. A life-cycle impact analysis will be developed based on the prototype operation, on the results of empirical analysis, and on an analysis of modeling and simulation.

1.3.3 Equipment use

This report focuses on the efforts of the Materials Formulation and Testing Team, whose first major task was to investigate and define the range of properties of cementitious material suitable for the automated construction process. Working with NASA and academic personnel experienced in layered construction, the ERDC team members learned to use existing equipment prototypes in the laboratory to process and place concrete. This built knowledge and competency in using the existing material, process, and equipment.

1.3.4 Concrete properties development

Based on lessons learned in the laboratory, parameters were determined to define a range of material fresh properties to explore. A set of concrete mixtures were designed and studied to provide ranges of rheological properties, pot life, maximum aggregate size, and other feature such as the suitability of the material for use in various climates and environments. Such properties drove equipment requirements for mixing, processing, pumping, etc. in the automated construction system.

Early properties of the concrete material, which are predicted to be critical to the success of automated construction, will provide opportunities for material development, likely beyond the current industry state of the art. Where possible, admixture samples will be obtained as feedstock for concrete mixture design and testing. Research and development will focus on creating a material that will hold its extruded shape and that will be able to support subsequent layers of material and to provide the desired surface finish. Precise control over the fluid-to-solid transition (setting) was a chief development goal.

Finally, long-term property requirements of the concrete were determined from structural, durability, energy, protection, and other requirements. Material development targeted the desired hardened and long-term properties while maintaining the needed fresh state (fluid) properties. Ultra-high strength concrete (UHPC) may be adapted to automated construction for some applications. Foamed concretes created by air entrainment were also investigated. These concretes exhibit lower thermal conductivity and use less material at the expense of compressive strength.

Each of the material development phases was repeated iteratively with evolutions in the mixing, processing, and construction equipment. As the equipment increases in scale, the materials will need to be adapted to work with the new system. The type of mixing action and the working time associated with the process evolved. Further material development was needed as the system moved toward automation and toward full-scale placement in a field environment. Known properties of geopolymers (e.g., geopolymers foam concrete), adobe, and other indigenous materials were considered as eventual materials for use in ACES equipment. However, they were not tested in actual construction during the prototyping phase.

1.3.5 Concrete testing

Concrete mixtures used during developmental printing were tested in the laboratory. The following laboratory tests were completed to verify the performance characteristics and suitability for use with the ACES equipment:

- *Strength (Compressive, flexural, and splitting tensile).* Compressive strength is the most common property used for routine verification of materials and quality assurance activity. A measurement of flexural strength is needed to determine appropriate criteria for use in vertical structures. Splitting tensile strength is also necessary for structural analysis. Bond strength may be an important property particularly during construction because the material is placed in layers; if multiple layers are needed, the impact of bond strength becomes even more important.
- *Time to set*. This parameter will have a high impact on production speed for ACES equipment.
- *Workability*. This is a basic test to determine how long the material remains workable for placement, particularly as it is pumped and extruded through a nozzle.
- *Freeze-thaw durability*. Subject test beams are cast from rapid setting material to test freeze-thaw cycling. Test early age beams to simulate an environment where a rapid temperature change occurs soon after placement.
- *Drying shrinkage*. Shrinkage of the concrete after placement is tied to material performance and potential for cracking.

Ultimately, the goal of this phase of work was to be able provide guidance to ACES operators on the best concrete mixture design for locally available materials. It will also serve as a foundation for future research into the increased use of indigenous materials.

1.3.5.1 Rheology and setting testing

Following the early developmental work on admixtures and mixture designs, a second effort was made to better quantify the effects of individual admixtures on concrete rheology, setting, and early age strength. Tests were performed using the ICAR rheometer, a penetrometer (ASTM C403), and a compressive load frame. The results of these tests informed critical decisions to adjust and simplify the concrete mixtures used during large-scale prototype operation.

1.3.5.2 Full-scale flexural testing

The ACES 2 prototype printed 16-ft. long reinforced concrete beams containing varied combinations of steel rebar, basalt rebar, aramid mesh, and basalt mesh. Following an adequate curing period, the beams were lifted into a custom load frame and subjected to destructive flexural tests using a hydraulic actuator attached to a strong reaction wall. The tests exposed several deficiencies in conventional reinforcement schemes, offering the opportunity for follow-on work to improve printed element reinforcement design.

1.3.5.3 Diagonal compression testing

Printed wall sections of approximately 3-ft. on each side were subjected to diagonal compression tests to determine their response to shear loads. Additional specimens were subjected to uniaxial compression tests in different planes relative to the printing direction. The ultimate strength and failure behavior closely followed mechanical models and typical behavior of conventional masonry piers, which may simplify future the incorporation of printed elements into existing seismic design code.

1.3.5.4 Blast load simulator (BLS) testing

Wall sections were tested to determine resistance to simulated blast loads. The ERDC BLS is a state-of-the-art facility for blast effects research. At the heart of the facility is the BLS, a compressed gas driven shock tube, used to simulate air blast loads. The BLS is designed to simulate the positive and negative phases of the blast pressure waveform for explosive yields up to

20,000 lbs. at peak reflected pressures up to 80 psi. The facility includes ⅓ scale and $^1/_{12}$ scale testing devices and a model fabrication shop to support operations.

Many construction materials including concrete, brick, and concrete masonry unit (CMU) wall sections have been tested in the BLS in various configurations, with and without reinforcement. Previous experimental results provide a broad database for gauging the performance of test sections generated using the ACES approach. Comparisons can be made, for example, with existing data using various monolithically cast concrete panels such as those made from UHPC or from concrete made with locally available or indigenous materials specific to a given area of operations.

While BLS tests of straight wall sections are reported here, of particular interest for the ACES program is the possibility of testing curved wall sections. Automated construction provides the capability of producing curved structural walls, and scaled sections can be fabricated having a desired radius of curvature. Curved walls are anticipated to provide increased protection against blast; measuring their performance would be a first of its kind experiment in the BLS.

2 Investigation of Concrete Mixtures for Additive Construction

2.1 Introduction

2.1.1 Background

Construction processes, in general, are labor intensive and potentially dangerous, making them ideal for automation. To reduce risk to personnel in the field and overall logistic requirements of construction, this work investigated large-scale automated additive manufacturing processes (e.g., 3D printing with concrete) for construction applications, also referred to as "additive construction." A number of recent research publications has described different methods for additive construction processes, such as *D-Shape* (Cesaretti et al. 2013), *Digital Construction Platform* (Keating et al. 2014), *Concrete Printing Being Developed at Loughborough University* (Lim et al. 2011, 2012), and *Contour Crafting* (Khoshnevis 1999, Khoshnevis et al. 2006).

Additive manufacturing is a rapidly growing technology. However, the literature regarding its use in large-scale systems using concrete material extrusion is somewhat limited. Much of it focuses around non-traditional concrete mixtures or investigations into the use of mortars. For instance, the work being done at Loughborough University investigates the use of mixtures that use no coarse aggregate, which, strictly speaking, is a mortar (Le et al. 2012b). Some of the work presented by researchers at USC investigates concrete using synthetic aggregate such as glass beads (Di Carlo 2012). Since the ultimate goal is to employ an automated construction system in a variety of environments and locations across the globe, it is desirable to use concrete mixtures comprised of aggregates, binders, and other materials that are commonly found worldwide and that can be tailored to available raw materials.

A variety of commercial materials are available worldwide that can be added to concrete to impart desired fresh and hardened properties. Since the present application will require a combination of fresh and hardened properties that are different from those needed for traditional concrete usage, this work considered several means of concrete modification. The Federal Highway Administration's National Concrete Pavement Technology Center provides a publication with broad guidelines for the use of such materials in concrete (Taylor et al. 2007). Drawing from this document, Caltrans' Guide for Design and Inspection of Concrete also provides a succinct table that lists the effects of various concrete additives on the properties of concrete (Caltrans 2010).

2.1.2 Objectives

The primary objective of the materials and testing stage of this research was to qualify a conventional concrete mixture for large-scale material extrusion in additive construction, or 3D printing with concrete, on a structural scale. A conventional concrete mixture is defined here as one that uses naturally occurring coarse and fine aggregates, standard portland cement, a minimum of admixtures, and conventional mixing techniques.

A trial traditional mixture was determined using the "weight-method," which required the trial mixture to display the following properties:

- Flow in the fresh state must be sufficient to allow pumping and extrusion through a narrow nozzle (nominally 1.75 in. square).
- Slump must be minimal to allow for shape stability after extrusion.
- The coarse aggregate size (⅜ in. was chosen) must be small to minimize the possibility of clogging during extrusion.
- Early properties, notably setting time, must be controlled to allow each layer of construction to support subsequent layers.

2.1.3 Experimental method

Starting with a typical concrete formulation, several additives to the concrete, including chemical admixtures and supplementary cementitious materials (SCMs), were investigated based on their ability to provide the desired properties listed above. Fly ash and silica fume were investigated as SCMs because of their ability to influence the rheology of concrete due to their small particle size and round particle morphology (Li et al. 2009; Peled, Cyr, and Shah 2000). It was further expected that fly ash and silica fume would aid in controlling compressive strength development, depending on the percentage of cement substituted (Raharjo, Subakti, and Tavio 2013; Mohamed 2011). In light of the lack of traditional concrete reinforcing bars in the additive construction process, discrete fiber reinforcement was investigated due to its potential to mitigate shrinkage cracking and increase tensile and flexural strength (Shah 1991, Olivito, and Zuccarello 2010). Relatively short fibers, nominally ½ in. long, were chosen to minimize flow problems. Bentonite was investigated for inclusion at low addition rates due to its potential for improving fresh shape stability, as noted in reports of bentonite's use in slip-forming (Tregger, Voigt, and Shah 2007). A polycarboxylate-based superplasticizer (SP) was also investigated to improve the fresh concrete workability at low water content without decreasing concrete strength.

A series of tests was performed on various concrete mixtures to explore their applicability toward the additive construction process. To that end, the mixtures were tested for flow, setting time, and early compressive strength.

2.2 Materials

2.2.1 Conventional mixture designs

A baseline trial mixture, labeled "A0," was proportioned using traditional concrete ingredients and was selected as a starting point for testing. The selected starting point was a mixture that included a conventional or typical cement:fine-aggregate:coarse-aggregate ratio of about 1:2:3. A Type I/II portland cement was used in this study. The coarse aggregate was a ⅜-in. manufactured limestone, and the fine aggregate was manufactured limestone sand, both sourced from Calera, AL. A rheology-modifying admixture (RMA), Navitas 33, supplied by BASF, was included in the baseline mixture at a dosage rate of about 1300 mL per 100 kg of cement to provide increased workability needed for extrusion. Additionally, the following three modifications were made to the baseline mixture for testing:

- **A0:** Baseline concrete mixture
- **A1:** Increase in cement content to provide more paste
- **A2:** Addition of bentonite clay to improve wet shape stability
- **A3:** Addition of an SP to increase flow.

Table 2-1 lists the specific materials and calculated quantities, assuming a density of 2370 kg/m^3, which was based on the use of limestone aggregates in concrete. Material quantities are reported as the amount in kilograms required to produce 1 m^3 of concrete. The A0 mixture was prepared and loaded into the extruder apparatus, but was too stiff to press through the nozzle. Modifications A1-A3 were made in an attempt to increase the flow, but none of these measures were sufficient to achieve the desired extrudability because of the high content of ⅜-in. limestone aggregate.

Table 2-1. Conventional mixture proportions, kg/m^3.

Mixture	Water	Type I/II Cement	Limestone Sand	Limestone ⅜-in.	RMA	Additive Type	Additive Amount
A0	223	358	790	994	4.5	None	—
A1	208	441	736	979	5.6	None	—
A2	211	447	746	939	5.7	Bentonite	22
A3	213	451	752	946	5.7	SP	2.9

2.2.2 Non-conventional mixture designs

After the conventional mixture design failed to produce sufficient flow characteristics for extrusion, the amount of coarse aggregate was significantly reduced while the fine aggregate was increased. These adjustments led to a non-conventional extrusion mixture. Where the conventional mixture had a cement:fine-aggregate:coarse-aggregate ratio of about 1:2:3, the extrusion mixture was chosen to have a ratio of 1:3:1 and a water-to-cement ratio (w/c) of about 0.5. Like the A0 mixture, the second control mix, labeled B0, additionally contained the Navitas 33 RMA at a dosage of about 1300 mL per 100 kg of cement. Furthermore, this B0 mixture was varied six times with one additional additive in each iteration. Additives were obtained from the following sources:

- metal fiber from Baumbach
- nylon fiber from Nycon
- SP was ADVA® 190 from W.R. Grace
- Class C fly ash from Redfield, AR
- bentonite clay was Aquagel from Baroid
- silica fume was Force 10000 D from W.R. Grace.

Table 2-2 lists these mixture proportions as the amounts (kg) required to produce 1 m^3 of concrete on a basis of 2370 kg/m^3. The fiber contents in mixtures B1 and B2 were not included in the volumetric calculation; the reported equivalent amounts of fiber were added to the freshly mixed concrete:

- **B0**: Control extrusion mixture
- **B1**: B0 with ½-in.-long metal fiber reinforcement added
- **B2**: B0 with ½-in.-long nylon fiber reinforcement added
- **B3**: B0 with SP added
- **B4**: B0 with fly ash replacing 20% weight of cement
- **B5**: B0 with bentonite clay added
- **B6**: B0 with silica fume replacing 10% weight of cement.

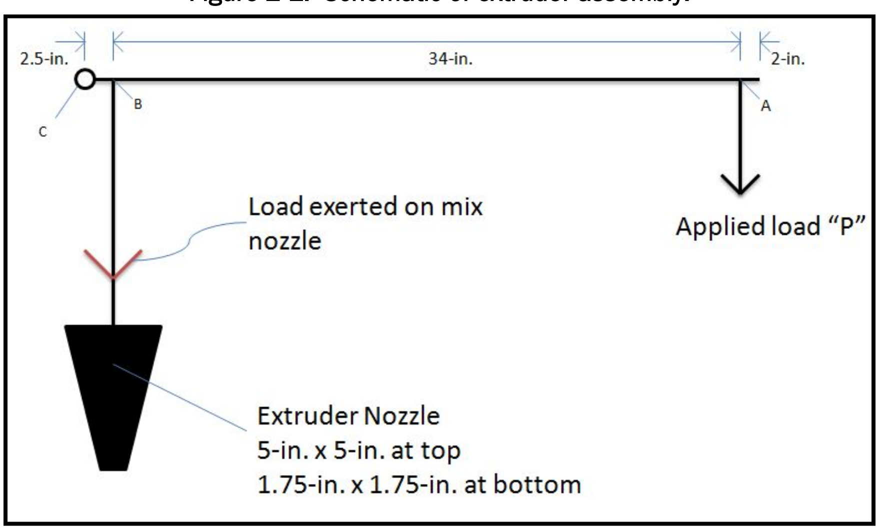
Table 2-2. Non-conventional extrusion mixture proportions, kg/m³.

Mixture	Water	Type I/II Cement	Limestone Sand	Limestone ⅜-in.	RMA	Additive Type	Additive Amount
B0	215	430	1290	430	5.4	None	–
B1	215	430	1290	430	5.4	½-in. Metal Fiber	39
B2	234	426	1278	426	5.4	½-in. Nylon Fiber	5.3
B3	215	429	1287	429	5.4	SP	4.3
B4	215	344	1290	430	5.4	Fly Ash	86
B5	232	422	1267	422	5.3	Bentonite	21
B6	215	387	1290	430	5.4	Silica Fume	43

2.2.3 Method

For concrete to be applicable to additive construction, it must be possible to extrude the concrete mix through a nozzle. To mimic the extrusion conditions, researchers chose to examine how the mixtures would pass through a common clay extruder. A Bailey Ceramics Standard 9 clay extruder assembly was selected to qualify the test materials based on extrudability. This apparatus was chosen because the rheology of clay and of fresh concrete are relatively similar, and the manual extrusion process is simple and cost effective. The clay extruder assembly was modified by welding a tapered nozzle that reduced to a 1.75 x 1.75-in. opening at the end so as to mimic the opening for the additive construction extrusion nozzle for the large-scale 3D printer that was being designed concurrently with this materials study. Figure 2-1 shows a simplified schematic of the extruder.

Figure 2-1. Schematic of extruder assembly.



Each fresh concrete mixture was loaded into the extruder and pressed through the outlet by manually pulling the arm, thus applying a load to the plunger and forcing the test material through the funnel. This test method, shown in Figure 2-2, provided a qualitative and comparative indicator of the suitability of each material for a simple extrusion process. The apparatus did not specifically quantify the load applied to the mixture and, therefore, did not measure the pressure required to extrude each concrete mixture.

Figure 2-2. Mixture passing through extruder.

2.2.4 Physical property testing

After preparing each batch of material and qualifying it for extrudability as described above, materials that were considered suitable were put through a series of standard empirical tests. A drop table test was performed for each mixture in accordance was American Society for Testing and Materials (ASTM) Standard C1437, with the table conforming to ASTM C230, to measure the relative flow characteristics. Initial and final times of setting were measured using the Vicat method according to ASTM C191. Sets of 2-in. cubes were prepared from each material, and the specimens were cured at room temperature in a 100% humidity environment. Unconfined compression testing was performed on the cured cubes in accordance with ASTM C109, with six cubes tested at each condition. Finally, to quantify the flexural strength of each mixture, a flexural strength test was performed in accordance with ASTM C78.

2.3 Results

2.3.1 Extruder testing

All four of the conventional concrete mixtures listed in Table 1-1 were qualitatively evaluated using the extruder assembly. A0 was prepared with a w/c of 0.6, but the mix locked up in the extruder funnel and excessive bleed was observed under the applied pressure. An attempt was made with A1 to increase the paste content by adding cement while alleviating bleed by reducing w/c to 0.47; however, the mix would not pass through the extruder apparatus. A2 and A3 included bentonite and SP, respectively, to test for improvements in extrudability. While the modified mixtures behaved somewhat more favorably compared with A0, none of them offered a reasonable degree of extrudability in terms of a large-scale material extrusion for additive construction. It was determined by inspection that the coarse aggregate content, which was too high, was causing interlocking of the aggregate and clogging in the funnel section of the device. Additionally, an unacceptable degree of bleeding of the concrete was observed when pressure was applied via the plunger mechanism. As such, no further tests were performed on the conventional mixture designs (A0, A1, A2, and A3).

The non-conventional concrete mixtures listed in Table 2-2 were also qualitatively evaluated using the extruder assembly and visually inspected for suitable flow characteristics. As a result of changing the cement:fine-aggregate:coarse-aggregate ratio to 1:3:1, all of these extrusion mixtures could be pressed through the extruder assembly with a reasonable effort. An estimate of the amount of pressure required to extrude the concrete was also made. Without an apparatus to quantify the load applied to the fresh concrete and thus the amount of pressure required to induce extrusion, a qualitative rating of 1 to 5 was assigned to each material based on the relative ease with which it was extruded. A rating of 1 indicated the mixture was very difficult to extrude, and a rating of 5 indicated the mixture was very easy to extrude. Table 2-3 lists these ratings.

Table 2-3. Rating of mixture extrudability (1=worst, 5=best).

Mixture	B0	B1	B2	B3	B4	B5	B6
Rating	1	4	2	5	4	1	3

Although the B3 mixture containing the superplasticizer was very easy to extrude, it was much too fluid and exhibited almost no shape stability; therefore, B3 was not tested further. The water content of the B3 mixture should be reduced if it is to be considered for additive construction. The addition of steel fibers seemed to increase the flowability of the mixture unexpectedly, as the B1 material extruded well compared to the control material, B0. The B2 material containing nylon fibers flowed better than the control, but not nearly as well as B1 with the steel fibers. Note that the water content was increased in B2 to obtain suitable flow because of the affinity of nylon for water. In each material containing fibers, the shape stability of the material after extrusion was improved over the B0 material. The replacement of a fraction of the portland cement with fly ash (B4) and, separately, silica fume (B6) improved extrudability relative to the control material. The water content was increased in mixture B5 because the bentonite absorbed a significant amount of water thereby drying the concrete. Surprisingly, even with the extra water, the addition of bentonite did not appear to help the overall flow. The bentonite did, however, aid in shape stability of the extruded material, which is an important consideration for an extrudable material for additive construction.

2.3.2 Drop table test

The non-conventional extrusion mixtures, excluding B3, were evaluated for flow using the drop table test. After forming the standard cone shape and imparting 25 drops of the table apparatus, the spread of each material was measured in four locations according to the standard method, at angles of 0, 45, 90, and 135 degrees. The flow number was determined as a percent of the original cone base diameter by averaging the four measurements for each material. Table 2-4 lists the flow number results.

Table 2-4. Flow numbers from drop table tests.

Mixture	B0	B1	B2	B4	B5	B6
Average Spread	20%	26%	26%	31%	16%	14%

Most of the extrusion mixtures exhibited medium to high flow (spread) in the drop table testing. Test B4, with fly ash, flowed the most, followed by the two samples containing short fiber reinforcements, B1 and B2. Tests B5 and B6 exhibited lower flow, corresponding to good shape stability, meaning that they spread out very little under multiple impacts. It was expected that fly ash would increase flow, while silica fume would reduce flow (Taylor et al. 2007, Caltrans 2010). Note that there seems to be little correlation between the qualitative extrudability rating reported above and the flow measure from the drop table. The key difference in these two flow evaluation methods is that the extruder method applied a steady stress, while the drop table imparted multiple impulse stresses.

2.3.3 Time of setting

The time of setting by the Vicat method was performed for each of the non-conventional extrusion mixtures with the exception of B3. For each test, the fresh concrete was sieved through a No. 4 sieve to remove coarse particles in accordance with ASTM C191. Samples of B1 and B2 were collected for Vicat testing before the addition of fibers; therefore, B0, B1, and B2 samples were essentially the same, and the results provide an indication of the test variability. Table 2-5 lists the initial and final set results in minutes. While most of the setting times were about the same for the mixtures, the initial set was delayed somewhat in B5 containing bentonite, and in B6 containing silica fume. The delay in B5 could be due to the increased water included to achieve consistent flow, while the delay in B6 may be attributed to the reduced cement content since silica fume was added as a cement replacement. No delay in setting was observed in B4, which included fly ash, and which was consistent with expectations (Taylor et al. 2007, Caltrans 2010). Generally, time of setting is an important consideration for large-scale concrete extrusion in an additive construction application because it indicates workability time as well as the time required for the deposited layer to begin gaining structural capacity to support subsequent layers placed on top of it. Though not studied here, setting time can be increased or reduced, according to the needs of the full-scale process, by the use of chemical accelerators or retarders.

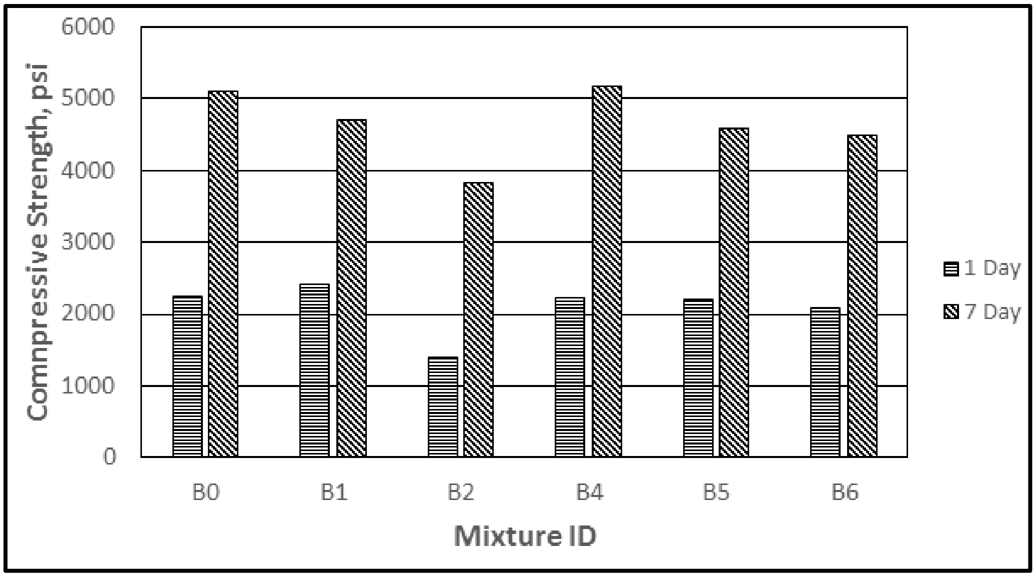
Table 2-5. Vicat time of setting, minutes.

Mixture	B0	B1	B2	B4	B5	B6
Initial Set	128	108	115	113	145	144
Final Set	192	183	205	215	235	230

2.3.4 Compressive strength testing

Unconfined compression testing was performed on each non-conventional extrusion mixture with the exception of B3. Two-inch cube samples were used to evaluate B0, B4, B5, and B6, while B1 and B2, which contained fibers, were evaluated by preparing 3x6-in. cylinders. The unconfined compressive strength tests of the materials were performed at 1- and 7-day ages. The values charted in Figure 2-3 reflect the averages of six compression test results at each condition, i.e., six specimens were tested instead of the typical three samples per test condition.

Figure 2-3. Unconfined compressive strength results.



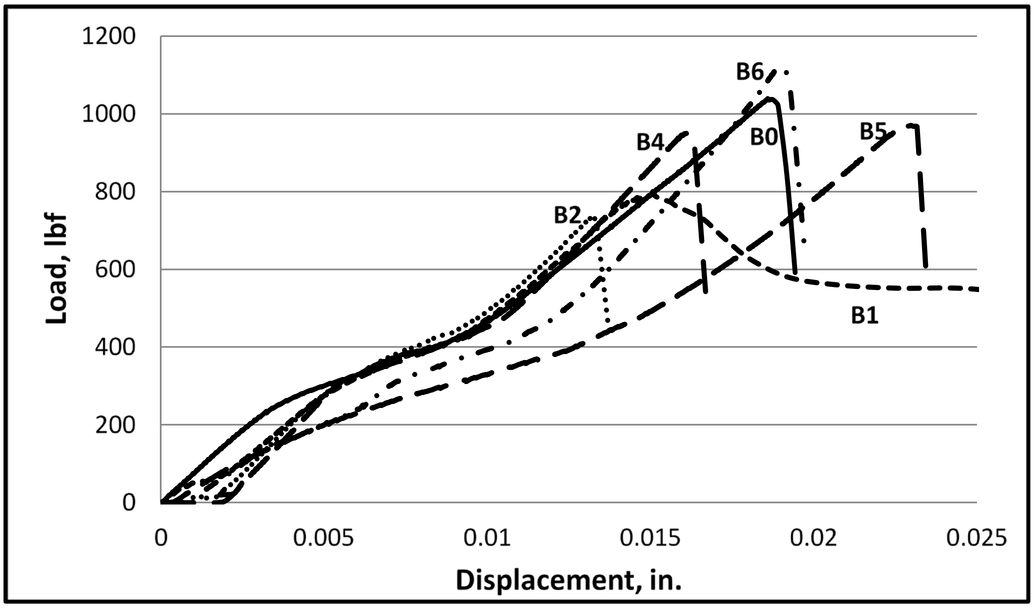
Generally, for the structural purpose of supporting layers in the case of additive construction, all of the mixtures were sufficiently strong, and there was not a large variation in strength. The lowest strength was exhibited by B2 containing nylon fibers. This could be due to the additional water that was added to this mixture to get a workable material. However, a similar amount of additional water was included in B5 containing bentonite without the corresponding decrease in compressive strength.

Another rationale for the strength decrease with nylon fibers is that the fibers themselves are low modulus (as opposed to the steel fibers, B1) and that they act as defects in the concrete matrix under compression. The reinforcing fibers in B1 and B2 did not increase the compressive strength compared with the control B0. This is because the test reports the peak strength; the reinforcing fibers are expected to engage after crack formation resulting in improved tensile softening behavior. The independent inclusion of fly ash (B4), bentonite (B5), and silica fume (B6) did not notably alter the compressive strength compared with the control at 1 or 7 days age. One favorable observation that may be drawn from the data shown in Figure 2-3 is that the use of additives as means to improve the flow and shape stability of the fresh concrete was not significantly detrimental to the concrete's structural properties. This tolerance is important for large-scale concrete extrusion in additive construction because it allows for the addition of a variety of flow aids to enable the inclusion of coarse aggregates while designing materials with the desired workability properties.

2.3.5 Flexural strength tests

Flexural tests were performed on one beam sample from each of the non-conventional extrusion mixtures (excluding B3) at 7 days age. Beams were 3x3x12 in. and were tested in a three-point bending configuration with a 10-in. span and the load applied at mid-span. Figure 2-4 shows the flexural testing load and displacement data, for comparison.

Figure 2-4. Flexural testing load and displacement data.



The peak strength, *f*, was calculated for each beam using:

$$f = 3PL/2bd^2 \quad (1)$$

where:

P = the peak load
L = the span
b = the specimen width
d = the specimen depth.

Table 2-6 lists peak flexural strengths.

Table 2-6. Peak flexural strength, psi.

Mixture	B0	B1	B2	B4	B5	B6
Flexural Strength	577	441	411	528	539	623

All of the unreinforced materials (B0, B4, B5, and B6) resulted in similar peak flexural strength values. The samples that included silica fume, B6, achieved the greatest flexural strength. Like the compressive strength results, the flexural test observations imply that the additives do not significantly deteriorate the concrete structural capacity.

The results regarding the reinforced beam samples are more significant. The inclusion of metal fibers (B1) or nylon fibers (B2) was not expected to have much effect on the peak flexural strength. However, both of the reinforced beams were weaker in flexural testing than the unreinforced beams. The reason for this decrease in peak capacity was probably due to the effective decrease in the cross-sectional area of the concrete matrix with the inclusion of fibers. The two types of fiber reinforcements were expected to provide some post-peak load-bearing capacity, resulting in a softening behavior in the load-displacement curve. Residual capacity, after crack formation, was observed in the sample containing metal fibers. However, the load-displacement test data for the sample containing nylon fibers did not show post-peak softening; the reason for this is that a threshold setting in the load program had been exceeded after the first crack formation and the software ended the test rather than continuing to collect data during the softening behavior. The post-peak response indicated that the metal fibers provided some reinforcement by a crack-bridging mechanism. Crack-bridging was visually observed in the samples containing nylon fibers, but the response was not measured because the test was terminated early.

2.4 Conclusions

This stage of work concluded that a conventional mixture design containing a typical proportion of coarse aggregate will not be adequate for additive construction applications because of insufficient flow through a nozzle apparatus. To allow for adequate flow, the concrete material must include a large proportion of fine materials such as sand, but it can still incorporate a significant content of coarse (⅜-in.) aggregate, which is expected to reduce shrinkage. Chemical admixtures and additives appeared to have varying degrees of success in aiding flow and shape stability. The addition of fly ash provided the best improvement in flow, while the addition of bentonite provided the best shape stability. The use of superplasticizer significantly increased fluidity of the mixture, but its use should be accounted for by reducing the water content of the mixture in the future.

Experiments showed that the addition of short reinforcing fibers did not reduce flow, and in fact appeared to aid flow in most cases. The inclusion of fibers improved shape stability of the fresh materials to some extent; thus, fibers are expected to be beneficial in additive construction since they offer some degree of reinforcement in both the fresh and hardened states. Considering that the nylon fibers are hygroscopic and tend to absorb water from the mixture, it would be of interest to use hydrophobic fibers such as polypropylene in the future.

Little correlation was observed between the results of the empirical drop table test and the qualitative extruder test. Although both the extruder and the drop table were used to determine flow characteristics of each material under some externally applied stress condition, there were two notable differences in these tests: (1) the extruder test provided a degree of confinement due to the presence of the funnel, as opposed to the unconfined condition experienced in the drop table test, and (2) the extruder test relied on a steadily applied pressure to induce flow, whereas the drop table produced a repeated acute stress, like an impulse load.

It was expected that the dynamic impact associated with the drop table played a key role in the difference between the two tests. A possible inference from this observation is that materials that flow poorly in the extruder but flow better on the drop table (e.g., B0, B2, and B5) could benefit from applied vibration during extrusion. The use of the drop table and the manual extruder apparatus together was intended to provide an easily attainable indication of how a test material would flow in an additive construction process that involves large-scale material extrusion of concrete through a nozzle. Next, experiments will be performed in an actual additive construction, or large-scale additive manufacturing setup using a custom 3D concrete printer. Then, observations from the applied test can be compared with the drop table and extruder results to better determine the utility of the two flow tests.

Broadly, this study demonstrated the ability to include coarse aggregates in a mixture for 3D concrete printing. Though the effects of the additives were evaluated one by one, an optimized mixture will likely include a combination of the testing additives, e.g., the base 1:3:1 concrete mixture, plus silica fume, plus SP, plus fibers. Such material combinations, as well as pumping through a real nozzle configuration, will be the next subjects of study.

3 Development of Mixture Formulas and Materials

3.1 Introduction

Automation continues to revolutionize the construction industry. Additive manufacturing ("3D-Printing") is the industry method for creating parts from computer designs through a layered deposition process that uses computer control. Additive construction scales up this technology to exploit the surface-forming capability of troweling, creating smooth and accurate planar and freeform surfaces out of extruded materials at a construction scale. This project applied additive construction to full-scale vertical structures built from concrete. This research used the AFCS B-Hut as the baseline for footprint, envelope volume, construction requirements, and sustainment requirements.

Candidate concrete mixtures are planned to use locally sourced materials, which will allow this technology to be used practically anywhere. While the material properties and quality vary, cement is available throughout the world. What is needed is to determine the material properties such as rheology and strength gain required for concrete to physically flow through the transport system, be extruded, and cure quickly enough to support the next layer. Procedures, protocols, and decision support tools are required for the concrete mixture design, along with suitable additives, to adapt locally available materials to the required rheology, curing time, and strength.

In Spring 2015, bench-level laboratory testing was conducted at the Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL) laboratory to gain a preliminary understanding of the material components and quantities needed to both create a baseline concrete mixture and explore other additives to improve the mixture's properties. The characteristics of the material in the plastic state were tested to determine the properties of the greatest interest to additive construction. Initial testing on the hardened strength properties was also conducted. Rushing et al. (in press) describe details of the bench-level testing. Building on this initial testing, the next stage of laboratory testing was conducted at the Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). Here, the focus of the testing was to down-select from the possible additives those that produce the best mixture characteristics, meaning the ability to flow through a nozzle, preserve shape stability, and gain strength at early age.

Selected additives commonly used in concrete construction included: fibers, bentonite (used in concrete construction to improve a concrete mixture's pumpability however, used here to improve shape stability), SCMs, and chemical admixtures. To begin this laboratory testing, single additives were added to the baseline mixture and tested. This report section describes the materials tested, test methods followed, and results obtained during the laboratory investigation. All of the materials used in the testing were commercially available. The cement type used in the baseline concrete mixtures was Type I/II, with the exception of Mix 2, which replaced the cement with Type III (high early strength) to test its effects; otherwise, all mixtures used Type I/II cement.

The testing methods conformed to existing ASTM standards. The exception to the testing methods was the extrusion test that followed CERL's experimental approach as a way to assess the flow characteristics of the concrete mixture. Based on the results of the single additives, a brief set of mixtures were tested using multiple additives. These follow-on tests focused on the material flow through the extruder apparatus. These mixtures, which contain multiple additives, were further adapted for testing in the 3D printing equipment at CERL.

3.2 Materials

Laboratory testing was done on a wide range of materials to down-select the most applicable materials for a baseline concrete mixture based on performance. This initial testing added a single additive to the baseline concrete mixture. The cement, and the coarse and fine aggregates were locally sourced from the Lebanon, NH area.

3.2.1 Cement

Portland cement was used as the primary cementing agent. In most cases the property of concern in any concrete mixture is strength gain. This conventionally comes from the formation of calcium silicate hydrate (C-S-H) crystals following the reaction of the minerals Alite (Tricalcium Silicate) and Belite (Dicalcium silicate) in portland cement with water. Alite is responsible for the early strength development and Belite is responsible for the late strength gain. The Alite and Belite reaction also results in the formation of portlandite (calcium hydroxide). During the hydration reaction of portland cement, there are several other reactions; however, the primary concern is the early age strength related to the above reactions.

The strength of the concrete can be modified during the mix design process by controlling water-to-cement ratio (w/c), where a lower w/c leads to higher strength concretes. It takes a w/c of about 0.4 to achieve full hydration of cement particles (Kosmatka, Kerkhoff, and Panarese 2003). However, with the use of superplasticizers it is possible to achieve much higher strengths with w/c closer to 0.26 (Le et al. 2012a).

In practice, five types of portland cement are available for use in North America, as categorized by ASTM C150 (ASTM 2012b):

- Type I: Normal (general purpose)
- Type II: Moderate sulfate resistance
- Type III: High early strength
- Type IV: Low heat of hydration
- Type V: High sulfate resistance.

The primary cement type used in the laboratory testing was Type I/II, known as a “general purpose” cement with moderate sulfate resistance, and used in the baseline and all of the test mixtures, with the exception of Mix 2. As a trial in Mix 2, ERDC-CRREL had on hand Type III cement (high early strength), which replaced the Type I/II cement. The cement used in the laboratory testing met the requirements of ASTM C150. The cement was manufactured by Lafarge Corporation and was available from the bulk supply of a local ready-mix plant. All of the testing used cement from a single lot.

3.2.2 Aggregates and water

Rough and angular aggregates provide mechanical interlock and improved paste to aggregate bond, but can lead to workability issues (Mindess, Young, and Darwin 2003; Kosmatka, Kerkhoff, and Panarese 2003). Rough and angular aggregates require a higher paste (cement and water) content to ensure a workable concrete at the same w/c (Kosmatka, Kerkhoff, and Panarese 2003). On the other hand, smooth rounded aggregates improve the workability of the fresh concrete. The mechanical properties of concrete are affected by large aggregates, and the rheology of the fresh concrete is affected by fine aggregates (Mindess, Young, and Darwin 2003).

A natural, washed concrete sand was used in all of the test mixtures. Gravel stone, locally described as “ledge,” with a metamorphic parent material, typically amphibolite, was sourced from a local quarry in Vermont. The gravel stone was processed through a crusher and screened to a nominal ⅜ in size. The material is rounded with a minimum of one fractured face. A small portion of the material was greater than ⅜ in. and was sieved out to maintain the gravel stone size to a maximum of ⅜ in. While the gravel material was washed, it was not free of fines, and that may have increased the mix water requirement somewhat to achieve a workable mixture. The aggregates met the requirements of ASTM C33 (ASTM 2013a).

A small quantity of the sand and gravel stone material was stored in the laboratory in bins and maintained at standard room temperature. This material was consistently dry. Larger stockpiles were stored in a covered shed outdoors. An initial moisture content for the sand and stone was taken from the laboratory bins to determine the quantity of mix water needed. When additional material was required from the outdoor stockpiles, the moisture content of each material was measured to adjust the mix water requirement.

Regular tap water was used for all of the mixtures. The water was used directly out of the tap and was not equilibrated to the ambient room temperature. The mean water temperature was approximately 49 °F.

3.2.3 Supplementary cementitious materials

SCMs are primarily added because they have a high silica content, which reacts with the portlandite from the Alite and Belite reactions to form C-S-H that gives concrete its strength. Additionally, SCMs, if added properly, can have positive effects on the workability of concrete (Kosmatka, Kerkhoff, and Panarese 2003). The types of SCMs investigated were fly ash and silica fume.

3.2.3.1 Fly ash

Fly ash is a by-product of burning coal and has a wide range of particle sizes (1 micron to 100 micron with 10-30% being above 45 microns) (Kosmatka, Kerkhoff, and Panarese 2003). The two types of fly ash used in concrete mixtures are Class C and Class F. Class C has pozzolanic properties and Class F has cementitious properties in addition to pozzolanic properties (Kosmatka, Kerkhoff, and Panarese 2003). Fly ash is a low reactivity cement replacement that leads to lower strengths; however, the use of fly ash leads to concretes with lower permeability (Hassen, Cabrera, and Maliehe 2000). Improved rheology is a result of the low reactivity and shape (spherical) of the particles.

3.2.3.2 Silica fume

Silica fume is a by-product of the silicon (Kosmatka, Kerkhoff, and Panarese 2003) and the zirconia (Richard and Cheyrezy 1995) industries. It is about 100 times smaller than the average cement particle and is spherical in shape (Kosmatka, Kerkhoff, and Panarese 2003). Silica fume can have negative effects on the fresh concrete rheology due to the fineness of the material requiring the use of a high-range water reducer (Kucharska and Moczko 1994). The small particle size allows silica fume to fill the interfacial regions near inclusions (aggregates, fiber, and conventional reinforcements) where excess water tends to form. Typically these regions tend to be weak and porous due to bleed water and insufficient packing of cement particles (Bentur, Diamond, and Mindess 1985). However, silica fume promotes denser interfacial transition zones and improved bonding between the bulk cementitious matrix and inclusion interfaces (Reda et al. 1999). Silica fume can achieve similar concrete properties at 10% replacement of cement when compared to a 30% replacement of cement with fly ash (Ha et al. 2012).

3.2.4 Clays

Small additions of clay in concrete mixtures has been gaining acceptance as a way to maintain shape stability in applications such as self-consolidating concrete and slipform paving (Tregger, Pakula, and Shah 2010). Bentonite, a clay that has primarily been used for cement grouting applications to reduce bleeding and improve imperviousness (Huang 1997), was considered.

3.2.5 Reinforcement

Fibers, which are a common design option and which are added primarily to prevent and suppress cracking (Bentur and Mindess 2007), have been considered to reduce shrinkage and plastic deformation in 3D printed concrete mixtures (Le et al. 2012a). In addition, adding fibers can facilitate the use of complex geometries (Kosmatka, Kerkhoff, and Panarese 2003). The types of fibers considered were steel, polypropylene, and nylon. In addition, an aramid fiber-reinforced polymer mesh was also explored. The aramid fiber mesh used in this testing consisted of thin dual strands of coated fibers in a square pattern with an opening size of approximately 1x1 in.

3.2.6 Chemical admixtures

A variety of chemical admixtures are available to achieve the desired fresh concrete properties. The following types of admixtures were considered:

- *Rheology-Controlling Admixture (RCA)*, which improves rheology, lubricates, responds well to vibration, and allows concrete to hold its shape under static conditions. This admixture is recommended for extruded concrete and low-slump concretes (BASF 2015d).
- *High-Range Water Reducers (HRWRs)*, which improve workability/rheology for high strength mixtures with low w/c (Mindess, Young, and Darwin 2003).
- *Accelerators*, which allow for early strength gain and are typically used for cold weather conditions, where a slow rate of hydration can prevent proper strength gain and potential for freezing (Mindess, Young, and Darwin 2003).
- *Shrinkage Reducers*, which reduce the amount of shrinkage that can occur as the concrete cures. The amount of shrinkage can potentially be lowered by 30-50% (Mindess, Young, and Darwin 2003).
- *Retarders*, which are typically used to increase the workable time during high temperature conditions, or when mass concrete structures are placed (Mindess, Young, and Darwin 2003). In terms of 3D printing these materials may be used to increase the length of time for printing (Le et al. 2012a).
- *Full-Range Water Reducer (FRWR)*, which is similar to hrWR, but offers a larger range of dosage rates (BASF 2015a).

All of the chemical admixtures used in this testing met ASTM C494 and were available from BASF. An admixture used to control mix rheology, MasterMatrix® 33, was used in the baseline mixture throughout all of the test mixtures. Designed for low-slump mixtures, MasterMatrix® 33 should aid in the flowability of the concrete mixture through the delivery system. The other admixtures selected for these mixture trials were: an accelerator (MasterSet® FP20), a shrinkage reducer (MasterLife® SRA 20*), a high-

* Shrinkage-Reducing Admixture (SRA)

range water reducer (MasterGlenium® 7700), an FRWR (MasterGlenium® 7500), and a retarder (MasterSet® R100).

3.3 Laboratory testing

3.3.1 Overview

This phase of laboratory testing was based on initial bench-level testing conducted at ERDC-GSL. Based on the information gathered, the laboratory testing conducted at ERDC-CRREL scaled up the size of the test mixtures from the bench-level to approximately a cubic foot. All mixing, curing, and testing was conducted at ambient air temperature. The test matrix of potential concrete mixtures was developed to compare the different mixtures containing a single additive to the baseline concrete mixture, and to quantify the characteristics of both the plastic and hardened properties with an emphasis on early age.

3.3.2 Test methods

Existing ASTM test methods were followed in this testing program. Since the focus of this laboratory testing was on the early age properties, modifications to the test methods consisted primarily of testing the specimens at earlier ages. Tests for compressive, flexural, and tensile strength were conducted at 4-hr, 8-hr, 24-hr, 7-day, and 28-day specimen ages. Tests on the material in its plastic state, such as slump, set time, and flow table, were conducted in accordance with the standard test method. Similarly, the tests on drying shrinkage specimen bars were conducted following the ASTM standard with an emphasis on early age. The focus was on the concrete material; therefore, the test specimens were fabricated using the concrete, and no material was sieved to remove the coarser stone fraction. The quantity of material in each test mixture, except where noted, was estimated to produce 15 compression strength cubes, five prisms for flexural strength, 15 splitting tensile cylinders, two drying shrinkage bars, and one set time specimen. Material used to measure slump was returned for use to fabricate test specimens; material from the extruder and the flow table was not reused. The techniques followed, along with any additional modifications to the standard method, are described further in each corresponding section later in this report. The test methods were:

- ASTM C78, *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)* (ASTM 2010)

- ASTM C109, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)* (ASTM 2013c)
- ASTM C143, *Standard Test Method for Slump of Hydraulic-Cement Concrete* (ASTM 2012b)
- ASTM C1437, *Standard Test Method for Flow of Hydraulic Cement Mortar* (ASTM 2013d)
- ASTM C403, *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance* (ASTM 2008)
- ASTM C496, *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens* (ASTM 2011b)
- ASTM C596, *Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement* (ASTM 2009).

The extrusion test, conducted on the freshly mixed material, followed the CERL method and was the only test without a formal standard. The extrusion test simulated the flow of the material at the point of delivery through the nozzle. This test was key in that it was typically the first test on the material immediately following mixing to assess the material's ability, under manual pressure, to flow through a square nozzle, and also to assess the effect of adjusting the quantity of mix water, and to observe the resulting material shape.

3.3.2.1 Test mixtures

Table 3-1 lists the laboratory test mixtures. The approach was to formulate a baseline mixture to which a single additive would be added. Bench-scale laboratory testing at ERDC-GSL used a Baseline mixture with ratios of cement: fine aggregate: coarse aggregate of 1:3:1 and a water-cement ratio of approximately 0.50. When a similar Baseline test mixture was prepared in the ERDC-CRREL laboratory using local materials, the result was a very stiff mix with very low slump that would not extrude. The Baseline mix was modified to further decrease the fine aggregate material fraction. A small test batch was mixed to check the consistency of the mixture before proceeding. The Baseline test mixture ratios of cement to fine aggregate to coarse aggregate were 1:2.3 :1. To determine the water-cement ratio without the mixture becoming too fluid, the mix started with a w/c of 0.45 and water was added incrementally. From this, a target w/c of 0.47 was chosen for the Baseline (Mix 1) concrete mix. The total quantity of mix water was adjusted based on the moisture content of the aggregates.

Table 3-1. List of concrete mixtures tested in laboratory.

Mix Number	Description
1	Baseline
2	Baseline using Type III cement
3	Baseline with Metal Fibers
3**	Baseline with Metal Fibers + Water
4*	Baseline with Nylon Fibers
5	Baseline with Polypropylene Fibers
6	Baseline with Fly Ash
7	Baseline with Bentonite
8	Baseline with High-Range Water Reducer
9	Baseline with Silica Fume
10	Baseline with Accelerator
11	Baseline with Shrinkage Reducer
12	Baseline with FRWR
13*	Baseline with Set Retarder

* Mixes 4 and 13 were proposed, but ultimately were not tested in the laboratory.
** Water was added to Mix 3 during specimen preparation due to dryness.

An RCA, BASF MasterMatrix 33, was used in the bench-level testing and was selected to be used in the Baseline concrete mixture to improve the fluidity. The manufacturer's recommended dosage range of MasterMatrix 33 is 2 to 12 fl oz/cwt (BASF 2015d). Based on the bench-level testing, the MasterMastrix 33 admixture was dosed at 20 fl oz/cwt, higher than the manufacturer's recommended dosage range. This Baseline test mixture (Mix 1) was used throughout the initial laboratory testing.

To this Baseline mixture, the following additives were tested as identified by the mix numbers. In Mix 2, a Type III portland cement was directly substituted for Type I cement at the same content. Type III cement is used when high early strength is desired. The inclusion of fiber reinforcement was used in Mixes 3 through 5. Steel fibers were added into Mix 3, Nylon Fibers were planned for addition in Mix 4, and polypropylene fibers were used in Mix 5. Mix 4 was not tested, as nylon fibers are hydrophilic resulting in an increase of the quantity of mix water needed (Rushing et al. 2016, Kosmatka, Kerkhoff, and Panarese 2003) compared to polypropylene fibers.

Regarding the inclusion of dry additives as a partial cement replacement, fly ash was used at a 20% replacement in Mix 6. In Mix 9, silica fume replaced the cement content at a level of 10%. Bentonite clay was added in Mix 7 at 5% of the cement content to aid shape stability and to improve flow.

Several different chemical admixtures, all BASF products, were added individually to the Baseline concrete mixture. Since the chemical admixtures were water-based, the quantity of mix water was reduced to offset the water contribution from the admixtures to maintain the target w/c. Mix 8 included MasterGlenium 7700 (BASF 2015b), a high-range water reducer for the purpose of maintaining slump and, ideally, reducing the mix water requirement. MasterGlenium 7700 was dosed at 5 fl oz/cwt, well within the manufacturer's recommended dosage rate of 2 to 15 fl oz/cwt. The accelerating admixture used in Mix 10 was MasterSet FP20. Accelerators are added to concrete mixtures to reduce the set time and to maintain workability.

In addition to being an accelerator, MasterSet FP20 acts as a water reducer. The accelerator was dosed at 60 fl oz/cwt, at the higher end of the manufacturer's recommended dosage range for use in mild conditions of 5-60 fl oz/cwt (BASF 2015e) A shrinkage-reducing admixture, MasterLife SRA 20, was used in Mix 11 and dosed at the lowest recommended rate of 0.5 gal/yd^3 (BASF 2015c). Mix 12 used an FRWR, MasterGlenium 7500. The FRWR was dosed 5 fl oz/cwt, well within the recommended dosage rate of 1 to 15 fl oz/cwt (BASF 2015a). Finally, plans were made to test a set retarder in Mix 13. The set retarder selected was MasterSet R 100 (BASF 2014). However, the laboratory testing supported the need for early strength characteristics that a set retarder could delay. Consequently, the set retarding admixture was not tested.

Two mixes (Mix 4 and Mix 13) were not tested during this initial laboratory investigation. As a result no data were presented for Mix 4 and Mix 13, although they will be included in the report for completeness.

To test for possible improvement in flexural strength to the Baseline mix, an aramid fiber mesh grid was added to a set of flexural strength beams. The mesh grid was added to the specimen so that it was oriented on the bottom during testing. This will not be reported as an additional mix, but as a modification to those beams tested with fiber mesh.

3.3.2.2 Mixing and specimen prep

All laboratory mixing, test specimen fabrication, and testing were conducted at approximately 70 °F. Once past a test mixture's initial set, test specimens for cube, flexural beam, and drying shrinkage bar specimens were stripped from their molds and placed into a curing box. Since the number of these molds was limited, they were cleaned and set up for the next set of test mixtures. Cylindrical test specimens for the splitting tensile test were fabricated in single-use capped plastic molds that remained at room temperature to cure. The plastic molds were stripped just before testing.

The assumption for this testing was that the concrete material would be supplied through a batch process. This approach of material supply may change during the project. A 2 cu ft revolving drum mixer was used in the laboratory testing (Figure 3-1). At the beginning of each day, the mixer was "buttered" before mixing a test mixture with a combination of cement, sand, and water to coat the interior of the drum. Excess material was dumped from the drum and then the test mixture was started. All mixing was completed under room temperature conditions. The total mixing time for each test mixture was approximately 5 minutes. Table 3-2 lists the materials for each test mixture, in the sequence they were added into the drum.

Figure 3-1. Revolving drum mixer (2 cu ft) used in laboratory testing.

Table 3-2. Procedure for laboratory mixing.

Step:	Activity
Butter the drum	Dump excess material out of drum
Start drum	
Add all pea gravel into drum	
Add half of the sand	Mix until combined
Add half of the water	Mix until blended
Add all cement	Mix until well blended
Add remaining sand	

Step:	Activity
Add remaining water	Withhold a small amount of water to rinse any chemical admixture container(s)
Add MasterMatrix admixture	Rinse container with reserved water and add rinse water into drum. Mix for 15 sec.
Add selected additive	If a chemical admixture withhold some reserved mix water to rinse the container

The age began when water and cement combined in the mixer.

The following method was used to prepare the test specimens.

Caution must be exercised when working with the metal fibers – they are *sharp*. Also, once dispersed in the mix, they protrude out in all directions. After the mixed material was discharged into the pan, cube specimens were fabricated on the concrete material.

For Mix 3 Metal Fibers, the addition of the metal fibers stiffened the mix considerably. This caused difficulty working with the mix and decreased the overall number of test specimens fabricated for all of the planned tests. Following the addition of the fibers, the extruder test clogged the nozzle. To improve the flowability of the material, water was added to the mix. These specimens were denoted with "Mix 3 + H2O" on the label. A total of six cube specimens were fabricated: three before the added water, and three after water was added. All six cubes were tested at 24 hrs. For splitting tensile testing, seven cylinders were fabricated before the water addition. Three cylinders were fabricated after the added water. The full complement of prisms were fabricated for flexural strength testing before the added water, one for each test age; no prisms were fabricated after the added water.

3.3.3 Plastic state

The term "consistency" is *the flow behavior, or rheology, of a fresh mixture* (Struble 2006; Kosmatka, Kerkhoff, and Panarese 2003) and is considered an important characteristic to ensure material uniformity and performance (Kosmatka, Kerkhoff, and Panarese 2003). For this initial laboratory investigation related to material for additive construction, consistency was qualified using tests for: extrusion, slump, flow table, and penetration. Results obtained from both the slump and the flow table to describe consistency are empirically-based as existing test methods do not yet characterize consistency.

"Workability" describes the level of ease or difficulty to place, consolidate, and finish concrete (Kosmatka, Kerkhoff, and Panarese 2003). As defined by ASTM C125-14 (ASTM 2014), workability is *that property of freshly mixed concrete that affects the ease with which it can be mixed, placed, consolidated, and struck off.* Factors that influence workability include: cement, consistency, sand, air entrainment, supplementary materials, chemical admixtures, and mixture proportions. Currently there is no widely accepted test method to measure this important concrete property, even though there are a number of products and technologies available used to enhance concrete workability (Daniel 2006). The slump test is commonly used to measure workability; however, it is limited.

Plasticity describes the ability to mold the concrete mixture (Kosmatka, Kerkhoff, and Panarese 2003).

3.3.3.1 Extrusion

The extrusion test was initially used during the bench-level testing at ERDC-GSL. Simply put, the purpose of the extrusion apparatus was to simulate a nozzle for a 3D printer, and to simulate how the concrete material flowed out of a receptacle that holds a small quantity of concrete and through a nozzle when some pressure was applied. Although there is no existing standard test method for this material/process, this qualitative approach provides an initial assessment of how the material flowed; and an opportunity to observe if the material might create an obstruction, and to study the shape stability of the material once it exits the nozzle.

The extrusion equipment consisted of a commercially available stainless steel clay extruder. The extruder consisted of a single welded square barrel with a removable plunger (Figure 3-2). A shackle was used to adjust the height of the plunger on the frame. The square barrel holds the material and a plunger arm was used to manually press the material through the nozzle located at the base of the barrel (Figure 3-3). The nozzle was fabricated at ERDC-CRREL and consisted of a square funnel that angled down to a square tube with an inner dimension of 1.75 x 1.75 in. The top of the nozzle overlapped the barrel and narrowed to a square interior opening of 1.75 in. with a small gap between the components (this was not a tight seal). The nozzle was mounted with a quick release system made from threaded eye bolts and secured with wing nuts for ease of assembly and disassembly. The extruder was mounted to an angular wooden frame that was clamped to a table to prevent movement and maintain a consistent height.

Figure 3-2. Laboratory extruder test equipment setup. The extruder was mounted to a triangularly-shaped wooden base. The bottom of the wooden base was secured to the table with a clamp (not shown). The nozzle was attached to the base of the barrel using a quick disconnect system. The inset (lower right) shows the interior dimensions of the square nozzle.

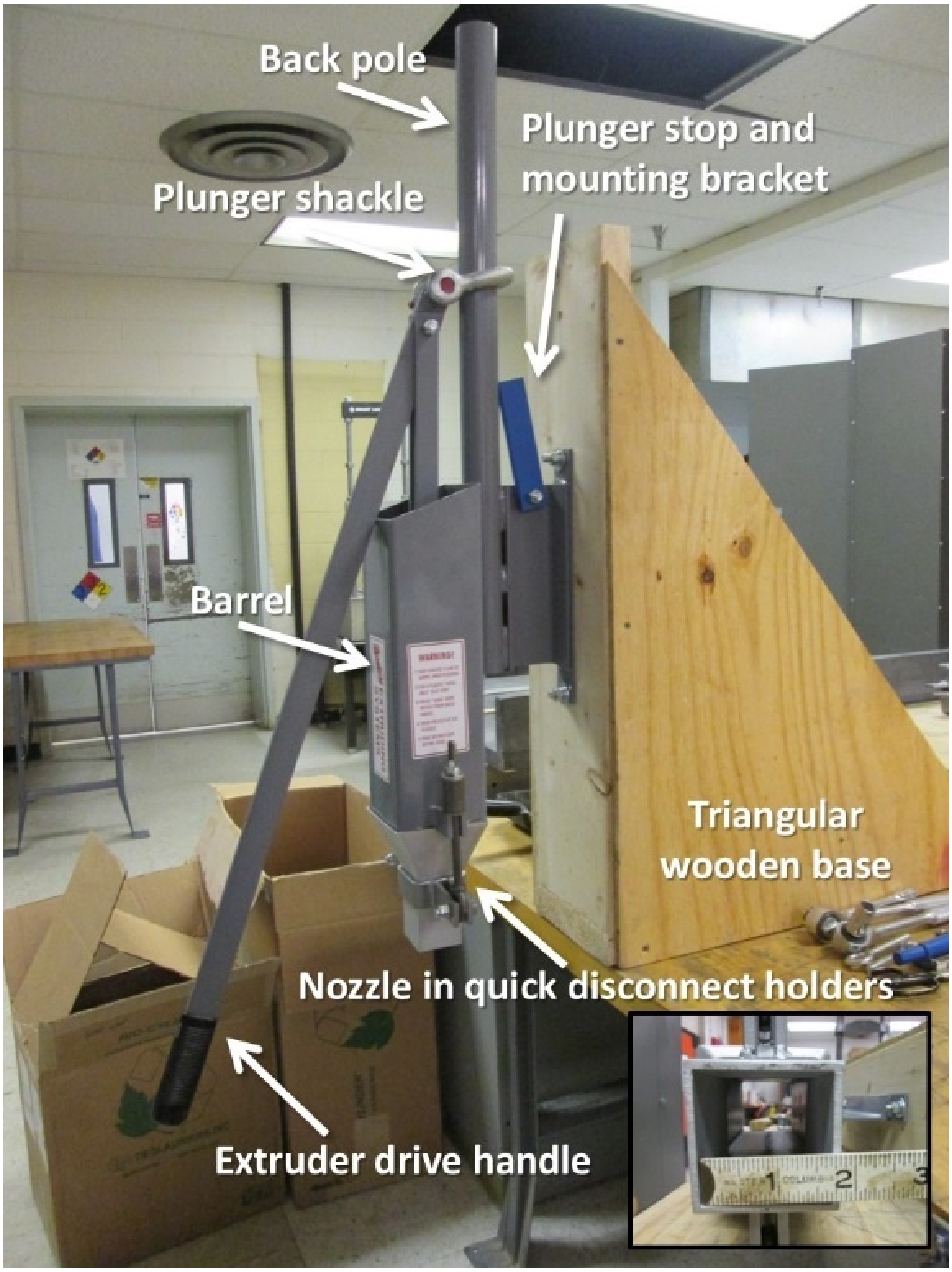


Figure 3-3. Clogged material removed from extruder.

Immediately after mixing, material was placed into the barrel and extruded onto a rigid surface into a single bead. The rigid surface consisted of a piece of plastic, roughly 2x2 ft, with a non-absorbable surface. The plastic was placed on a cart within inches from the base of the nozzle. The plunger was removed and the interior components were damped with water to prevent sticking. To prevent any material from falling through the barrel and the nozzle, the bottom of the nozzle was covered. The barrel was filled approximately one-third to half full with concrete material and the plunger arm was set to consolidate the material. The cover was removed at the bottom of the nozzle. The plunger arm was pulled down in a smooth motion using uniform force until it stopped. Simultaneously, as the material extruded from the base of the nozzle, the cart was moved slowly to allow the extruded material to form a single bead of material with a length of roughly 12 in. It is important at this point to not force the plunger arm. Time to complete the test is short – only a few seconds. For mixtures that clogged the nozzle, extra water was added to the mixture and the extruder test re-run to see if the flow characteristics improved. Once the test was completed, the barrel, plunger, nozzle, and board were cleaned to prepare for the next test mix.

The material was visually observed as it was extruded. As the plunger arm was moved, it was not uncommon for water to seep out through the gap between the bottom of the barrel and the top of the nozzle. In some cases, the material would become choked in the top of the nozzle where it narrowed to the square opening, preventing the plunger arm from any movement. At this point, the plunger arm was removed from the barrel and the nozzle was removed to clean out the clogged concrete material. Figure 3-3 shows an example of clogged material removed from both the barrel and the nozzle.

The extruder was the first screening test for all of the test mixtures. The test was performed primarily to observe how well the material flowed through the nozzle and maintained some semblance of form. Should the mixture be too dry, then additional water was added to improve the flow through the nozzle. No steps were taken to attempt to optimize the test mix based on the extruder test. Adjusting the flow characteristics of a mix will be addressed later, should the mix prove a possible candidate.

3.3.3.2 Slump

The concrete slump test is a widely accepted method for both laboratory and field use to monitor the consistency and workability of a mix in the plastic state. For additive construction, the material must have a consistency that can flow through the delivery system and through the nozzle, and that can provide shape stability during the layered construction process. Consistency will need to be maintained during the batching process. Any fluctuations in the material will require an understanding of how the mix fluctuates and how to address them. In this investigation, the slump test was used to compare the effects of a single additive to the baseline mixture. It is unclear if the slump test provides an initial indication of the shape stability of the mixture.

The standard test method, ASTM C143, *Standard Test Method for Slump of Hydraulic-Cement Concrete,* was followed in the laboratory testing. The test offers a comparison between similar mixtures to determine the influence on the consistency of varying material component proportions, which is the current industry method to describe "workability." Under controlled laboratory conditions, there is a relationship between the slump and strength; however, this relationship does not translate under field conditions (ASTM 2012b). The test is unsuitable for comparing dissimilar mixtures, mixtures with very low slump, and mixture that result when insufficient material is available. In standard portland-based concrete mixtures without additives, there is a direct relationship between the slump and water content for given proportions of cement, water, and aggregate. Consistency and workability may be impacted by cement content moreso than cement type. If the mixture contains too little cement, the workability is reduced; conversely, if the cement content is too high, the resulting mixture may be “sticky” and difficult to finish even though the mix could be considered workable (Daniel 2006). The water demand, and therefore the slump, may be impacted by increasing the content of fine aggregate (or coarse aggregate) due to the greater surface area; rounded aggregates tend to improve a mixture’s workability compared to particles with crushed or angular faces (Daniel 2006).

Other additives used to enhance concrete properties impact the slump. Chemical admixtures, in particular water reducers, are reported to decrease the water content of the mixture by 5-10% without adversely affecting the slump, and to increase strength (Kosmatka, Kerkhoff, and Panarese 2003). Kosmatka, Kerkhoff, and Panarese (2003) also assert that a higher slump may result when water-reducing admixtures are used with no reduction in the quantity of mix water; the effect is a rapid rate of slump loss that affects both the mixture’s consistency and workability.

The mixture’s slump is also affected by SCMs such as fly ash and silica fume. Fly ash is considered to improve the workability of a mix without impacting the shrinkage, and a mixture incorporating fly ash could reduce the water demand by 1 to 10% (Kosmatka, Kerkhoff, and Panarese 2003). Conversely, the low bleeding characteristics of silica fume may increase plastic shrinkage, and the increased surface area from its small particle size may increase the water demand (Kosmatka, Kerkhoff, and Panarese 2003). For mixtures with a low water-cement ratio containing silica fume, Neville (1996) suggests using a super plasticizer to keep the water demand low while yet retaining workability. In instances with very low slump mixtures, the flow test may be more suitable to the slump test (Neville 1996).

The test procedure for ASTM C143 consists of filling a cone-shaped mold with fresh concrete in three layers, and consolidating each layer before adding more material. Once the mold is filled, it is lifted allowing the mass of concrete to settle. The resulting reduction from settlement in the vertical height of the mass of concrete is measured and recorded. In the laboratory, the test followed the procedure specified in ASTM C143 with no modifications and a single slump test was conducted on each of the candidate mixtures. Figure 3-4 shows an example of the slump test conducted on a low-slump material. At the completion of mixing, the material was discharged into a large tub. The material sample for the slump test was taken from the tub concurrent with other tests. When the slump test was completed, the material was returned to the tub to be used to prepare test specimens. The slump was measured to the nearest ¼ in. No shearing of the material was observed or reported during the testing. Conventional concrete mixtures are considered uniform when the variability of the slump measurement is less than 1 in. (Kosmatka, Kerkhoff, and Panarese 2003).

Figure 3-4. Slump cone test on a low-slump mixture.

3.3.3.3 Flow table

Another test to measure the consistency of hydraulic cement-based mortars and pastes is the flow table. Laboratory testing was conducted on the unsieved concrete mixture. The test procedure followed in the laboratory was ASTM C1437 *Standard Test Method for Flow of Hydraulic Cement Mortar*. The test method is useful for comparing mixtures with different water contents and ingredients (Kosmatka, Kerkhoff, and Panarese 2003). This test is useful under both laboratory and field conditions, although in a field setting, it is not as commonplace as the slump test. The flow table is a fairly simple and inexpensive test to run, yet the results pertaining to the shear properties may be inadequate and difficult to analyze, and the overall significance of the test results is unclear (Kim, Cortes, and Santamarina 2007). In a conventional mortar mixture (Kim, Cortes, and Santamarina 2007), the role of the fine aggregate particle shape was found to play an influential role on the material flow, on how the particles packed together, and on the development of the frictional resistance. The flow table may be a way to characterize the consistency of a concrete mixture for additive construction. Similarly, it may be a useful method for quality control purposes to ensure consistency from batch to batch.

A single flow test was conducted on each mixture immediately after mixing was completed. In a study that examined the correlation between the flow table and the slump test, Smith and Benham (1931) suggested that the flow test may have greater sensitivity to changes in wetness for a given mixture. For additive construction, this level of subtlety may be valuable. The approach followed the test method where the mold was filled with a single layer of concrete, tamped during filling, and then leveled by striking off the excess. The table was dropped 25 times followed by four measurements with the caliper. For each concrete mixture, the sum of the four readings provides the flow table value (%).

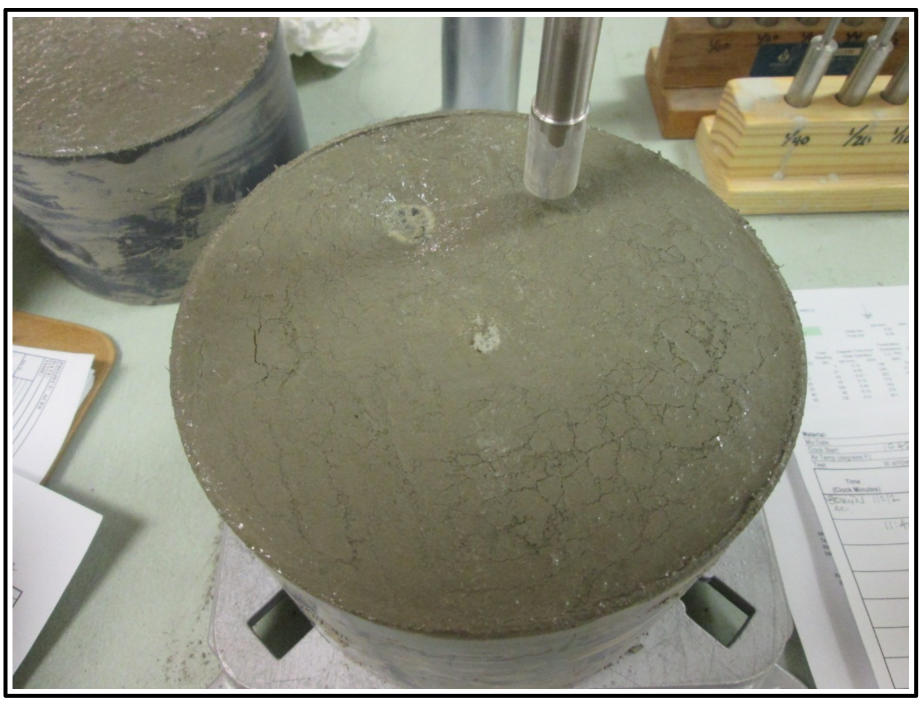
3.3.3.4 Time of set

A mixture's setting characteristics, or rate of hardening, directly affects the construction progress (Kosmatka, Kerkhoff, and Panarese 2003). The set time test is described in ASTM C403, *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*. The set time test determines the initial and final set times of a concrete mixture using an instrument to measure the penetration resistance as needles with varying surface areas are applied to the mixture with a loading apparatus. The penetration force is measured. Factors that can influence the setting time of a mixture include the water-cement ratio, admixtures, and temperature (Kosmatka, Kerkhoff, and Panarese 2003).

One set time test was conducted on each candidate mixture. In a departure from the standard method, this test was conducted using a sample of the mixture, i.e., unsieved material. This approach was selected as the mixtures used a smaller aggregate size of ⅜ in. and contained less coarse aggregate than a conventional concrete mixture; therefore, any interference between coarse aggregate particles and the needle was considered minimal. Moreover, the test was conducted on the full mixture. Because the testing was conducted for preliminary evaluation of the mixtures, only one set time test sample was prepared. The unsieved material was placed in a rigid 6 in. diameter, 4 in. high cylindrical container in a single layer, and was consolidated on a vibratory table for approximately 10 seconds, or until entrapped air was released. The first penetration reading was typically taken at 30-40 min from the time cement and water initially came in contact. Temperature readings of the sample and the room air temperature were taken concurrent with the first penetration reading. All penetration readings were conducted at standard room temperature. Air and sample temperatures were recorded periodically.

The testing apparatus, commercially available from Humboldt Manufacturing, was a hydraulic reaction-based penetrometer with a dial for the applied force readout, up to 200 lbf maximum. A standard set of penetration needles with customary bearing areas were used to collect the set time data. Figure 3-5 shows an example of the test.

Figure 3-5. Mix 1 Baseline set time sample set in measuring apparatus.



3.3.4 Hardened state

3.3.4.1 Compressive strength

The compressive strength of each test mixture followed ASTM C109, *Standard Test Method for Compressive Strength of Hydraulic Cement*

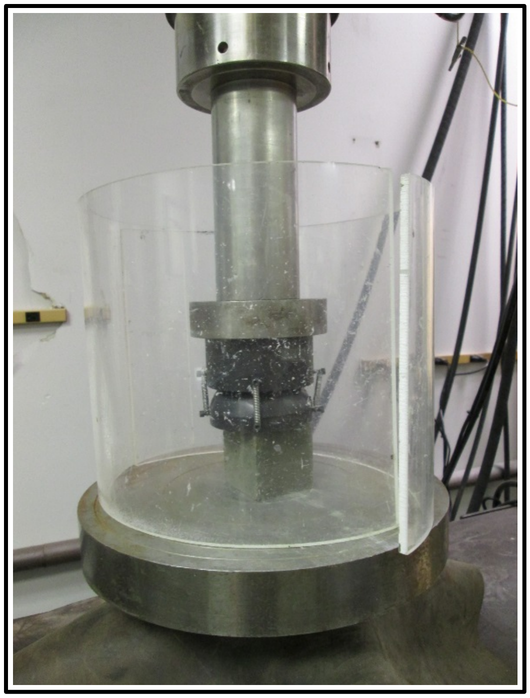
Mortars (Using 2-in. or [50-mm] Cube Specimens) with slight modifications. All cube specimens were fabricated from the concrete mixture and included a minimum of ⅜-in. coarse aggregate, not conventional mortar as indicated in the test standard.

After mixing, the material was discharged into the pan from which the material was taken to fabricate cube specimens. Three cubes were fabricated for each test age (15 cubes for each mixture). As per the standard, the concrete material was tamped into the mold in two layers. The molds were covered with plastic wrap to reduce moisture loss from the top face. The cubes remained in the molds until they could be safely removed without breakage. At 4-hr test age, three cubes were stripped from their molds. Almost without exception, the 4-hr test age occurred before the mix reached initial set so that at this early age, the cubes were fragile. The remaining cubes stayed in their molds to continue curing. The cubes tested at 8 hrs were also removed from the molds and tested. When the material had reached initial set and the cubes could be removed without breakage, the remaining cubes were stripped from their molds, placed into the moist curing box, where they remained there until testing.

For Mix 3 Metal Fibers, the addition of the metal fibers stiffened the mix considerably, making it difficult to work with the mix. In addition, the dryness of the mix made consolidation difficult. This decreased the overall number of test specimens fabricated for the planned tests and led to clogging while performing the extruder test. To improve the flowability of the material, water was added to the mix. These specimens were labeled as “Mix 3 + H2O.” A total of six cube specimens were fabricated, three before the added water and three after water was added. All six cubes were tested at 24 hrs.

Cube specimens were tested individually using a hydraulic-driven testing machine (Figure 3-6). The applied loading rate was 200 lbs/sec. The same loading rate was applied to all cube specimens at all test ages. Once the cube was positioned in the test apparatus, the bearing head was put in contact with the top surface of the cube only to apply a seating load. The cube was then turned on its side so the loaded side would be smooth from the sides of the cube mold (and not an irregular surface from the unconfined top). The time (sec), displacement (in.), and force (lbf) were continuously measured during the test from which the strain and stress were calculated.

Figure 3-6. Compression strength testing of a cube specimen.



3.3.4.2 Flexural strength

Flexural strength is a critical material property that will determine how the structure will perform when it is placed into service, and throughout its service life. Flexural testing conformed with ASTM C78, *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)* without any significant modifications.

Beam specimens used in the flexural strength testing were prepared for each concrete test mixture. The dimensions of the steel test beams were 3x3x12 in. The beam mold was filled in two layers and briefly consolidated on a vibratory table. The top of the beam was smoothed and leveled to ensure good paste coverage of the aggregate. The beam specimens were covered to plastic wrap to retain moisture. For each test mixture, one beam specimen was fabricated for each of five test ages (4, 8, and 24 hrs; and 7 and 28 days) for a total of five beams for each test mixture. At the 4 hr test age, the test beam was carefully stripped from the steel mold. For each test beam during testing, a continuous loading rate of 6.25 lbf/sec was applied (Figures 3-7 and 3-8). For Mixes 1, 2, and 8 at 4 hrs, the test beam broke prematurely either under its own weight or during pre-loading in the test apparatus. The first successful test age for Mixes 1 and 2 was at 8 hrs. However, for Mix 8, a second beam was tested at the 4-hr test age. Once the material had set up, all of the molds were removed and the beam specimens continued curing in the moist curing box. A continuous loading rate of 6.25 lbf/sec was applied during testing. Reported flexural strength values are from a single beam. For Mix 3 Steel Fibers, the five flexural test beams were fabricated from material before the additional mix water was added to aid material extrusion.

During beam fabrication for Mix 1 Baseline, a fiber mesh was added to test for possible flexural strength improvement (Figure 3-9). The mesh was added to five test beams; the beams were finished and the mesh inserted on the top. When set up for the testing, the beam was positioned so that the mesh was on the bottom (Figure 3-10) (one test erred with the mesh on top). Four beams with the mesh were tested at ages 4, 8, and 24 hrs, and 7 days.

Figure 3-7. Flexural strength testing of prism specimens.

Figure 3-8. Mix 1 Baseline flexural at 8-hr test age in the testing apparatus.

Figure 3-9. Aramid fiber mesh added to Mix 1 test beams.

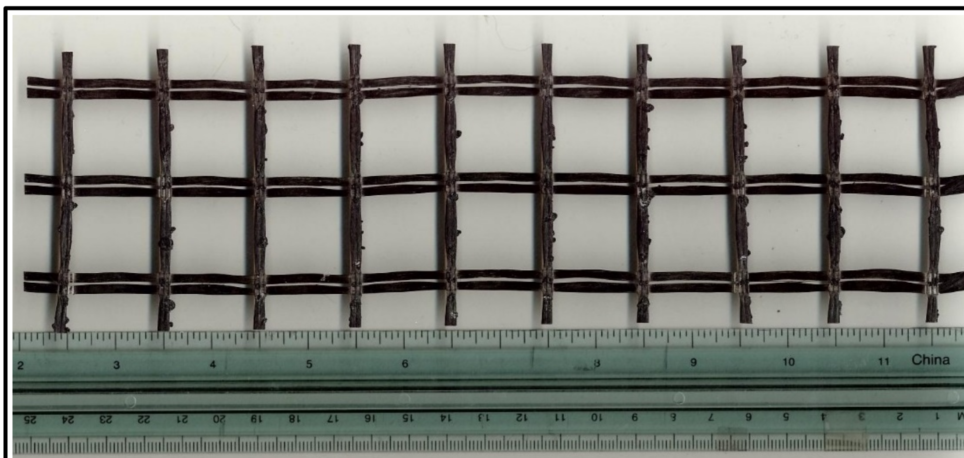


Figure 3-10. Test beam for 4-hr Baseline mix with aramid fiber mesh reinforcement.

3.3.4.3 Splitting tensile strength

Cracking in concrete is tied to the material's tensile strength (Mindess, Young, and Darwin 2003). In comparison, the material's compressive strength tends to be higher than the tensile strength. It is reasoned that, when loaded, the tensile failure of the concrete is the cause of crack initiation and propagation (Mindess, Young, and Darwin 2003). As applied to materials intended for additive construction, the tensile strength of the test mixtures will provide some insight into the potential for cracking, as well as the spacing of reinforcement. The laboratory testing conformed with ASTM C496, *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. In this indirect tensile strength test, the load is applied to a cylindrical test specimen to induce a tensile failure. No significant modifications were made to the testing procedure.

The test specimens were fabricated using plastic cylinder molds with dimensions of 3 in. diameter, 6 in. height. The molds were filled in two layers, consolidated on a vibratory table, leveled and capped to retain moisture. The test cylinders cured at ambient temperature within their molds. Test cylinders were stripped from their molds just before testing. For example, Figure 3-11 shows a test cylinder for Mix 3 at 24 hrs set up in the test apparatus. The angle of the photo does not clearly show the wood strips placed on the top between the cylinder and the load plate; and on the bottom between the cylinder and the rigid base. Figure 3-12 shows a completed test for Mix 7 Bentonite at 4 hrs. Figure 3-12 shows the early age condition of the test cylinder. This was not uncommon for many of the other test mixes at this early age. The low tensile strengths are also indicative of the fresh material. This was the case for Mix 1 Baseline where the test cylinders at the 4-hr test age did not come out of the molds cleanly, resulting in no test results for Mix 1 at that early age. However, Figure 3-12 does show the failure along the cross section of the cylinder (of Mix 7), which was a consistent type of failure for all of the test cylinders.

The reported splitting tensile strength is the average of the three cylinders (see Table 3-5 notes for exceptions). For Mix 3 Base + Steel Fibers, test cylinders were fabricated for test ages of 8 hrs and beyond from the mixture before the extra water was added. Three cylinders were fabricated after water was added.

Figure 3-11. Tensile strength test setup of a test cylinder for Mix 3 at the 24-hr test age.

Figure 3-12. Mix 7 Base+Bentonite splitting tensile strength test cylinder at 4-hr test age after failure.

3.3.4.4 Drying shrinkage

The drying shrinkage of the candidate concrete mixtures was tested in the laboratory following ASTM C596, *Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement*. This test measures the change in length of test specimens fabricated from hydraulic-based cement exposed to an environmental condition. This test method does not subject the test specimen to an externally applied force. For additive construction, this test method will provide an indication of the amount of shrinkage of the baseline concrete mixture with one additive. Factors that influence drying shrinkage include: cement content, the water-cement ratio, degree of hydration, aggregate elastic modulus, admixture types and dosages, relative humidity, concrete mass size and shape, and internal reinforcement (Goodwin 2006). Goodwin (2006) also discusses causes that can increase drying shrinkage of a mixture increases from any dust that is on unwashed aggregate, admixtures that increase the water requirement of a concrete mixture, and fly ash. The drying shrinkage for concrete mixtures containing up to 10% silica fume by mass of cement is comparable to control concrete moist cured for 28 days. Also, mixtures containing fibers have been shown to reduce shrinkage as they redistribute the interior stresses (Goodwin 2006).

While ASTM C596 specifies the use of mortar, the test was conducted using the unscreened concrete mixture. Drying shrinkage from loss of moisture for plain, normal weight concrete was reported by Goodwin (2006) to range between 400 to 800 microstrain.

This test repeated the mixtures initially conducted with the larger-scale testing. During the larger-scale testing, attempts were made to use a mixture of stainless steel and plastic molds. However, the plastic molds proved problematic and the results were discarded. In this duplicate laboratory testing, stainless steel metal molds were used to fabricate all of the specimen bars. Since smaller quantities of material were needed to fabricate the specimen bars, the mixture sizes were quarter-sized and were mixed in a 5-gal bucket using a handheld drill with a paddle. The smaller mixtures mimicked the same components and water-cement ratio as the larger-sized laboratory mixtures prepared in the revolving drum mixer.

Modifications to the standard method included the following:

- All specimen bars were fabricated and tested on the full concrete mixture, not mortar.
- The test mixtures used the concrete sand (the same as was used in the larger-scale testing).

Twelve mixtures were tested. Mix 1.2 was the Baseline mix that replaced a portion of the sand with Ottawa sand to observe any effects from using a uniform material.

All mixing was completed at ambient temperature and all materials were equilibrated to that temperature, with the exception of the mix water that was taken directly from the tap. The specimens were fabricated in stainless steel molds conforming to ASTM C596 (ASTM 2009) and C490 (ASTM 2011a) (Figure 3-13). A vibratory table was used to consolidate and distribute the mix within mold. The bars cured at ambient temperature and were removed from the molds after initial set when they were sufficiently hardened. This was approximately 4-6 hrs after mixing, earlier than the 24 hrs indicated in the standard. Four bars were fabricated for each concrete mixture. Some breakage of the test bars did occur during the course of either demolding or during handling. For each test mix, a minimum of two bars were tested. The interior dimensions of the molds are 25x25x285 mm, as per ASTM C490, *Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete.*

Figure 3-13. Stainless steel bar molds used to fabricate drying shrinkage bar specimens.

Data loggers were used to record the temperature and relative humidity of the curing box and the ambient room. Figure 3-14 shows a photo of the curing box. Measurements were recorded at a frequency of 15 min.; Figure 3-15 shows the hourly average. In keeping with the standard method, the specimen bars remained in the curing box until the age of 72 hrs. At that age, the test bars were removed from the curing box and placed on wiring shelves in the laboratory (Figure 3-16). Curing deviated from the standard because moist curing (but not with lime-saturated water) was used.

The test bar age was based on the time when cement and water were combined during mixing. Length comparator measurements were collected on the test apparatus (Figure 3-17) for each specimen bar as specified at the ages of 72 hrs, and after air storage of 4, 11, 18, and 25 days (or 7, 14, 21, and 28 days total age). In addition to the test ages specified, length comparator measurements were collected at the time the bars were demolded (just before placement in the cure box) and after the first 24 hrs of moist curing in the box (test bars were returned to the cure box after this measurement).

3.3.4.5 Mixtures

Mix 1 Baseline was re-mixed and called Mix 1R. Generally, the different test mixtures flowed well and were relatively easy to consolidate. The one notable mix was Mix 7 Bentonite, which was very stiff and required additional time to consolidate on the vibratory table. A flow table test was conducted on each mix immediately following mixing to observe repeatability between these mixtures and those from the larger-scale testing.

Figure 3-14. Curing box used in the laboratory testing to supply a moist curing environment.

Figure 3-15. Average hourly air temperature and relative humidity measurements of the air cure and curing box.

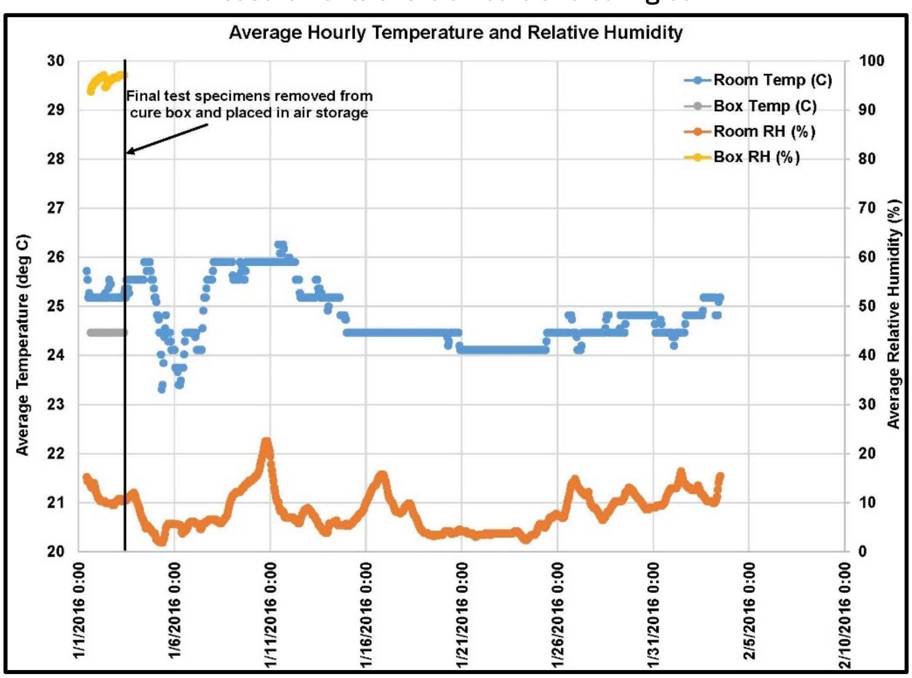


Figure 3-16. Test specimens were placed on wire shelving to continue air storage.

Figure 3-17. Length comparator apparatus with digital readout.

3.4 Plastic properties

3.4.1 Extrusion

Since there was no quantitative measurement, descriptive terms (such as "gritty") were used to describe a test mix that was dry to the touch and scraped the inside of the barrel when attempting to extrude it. Often, before the sample material was loaded into the barrel, a researcher would squeeze a handful to try to wring out any free water (a method similar to a field soil test). While not precise, this would often be an initial indicator that the test mix might flow through the extruder without clogging.

Figure 3-18 shows a series of photographs that show the test mixes through the extruder apparatus. Note that, in some cases, the material flowed somewhat easily through the nozzle in a continuous ribbon, then spread out and the upper surface would settle. For other mixtures, the ribbon would break into pieces or the top and sides would tear. In some instances, this was due to moving the cart too fast. However, it may also be due to the square nozzle configuration. Other nozzle configurations may be more suitable and should be considered for future testing.

What is needed is a more accurate method to quantify the flow characteristics of a material that is relatable for use in an additive construction application.

Figure 3-18. The extruder test for the test mixtures—illustrated.

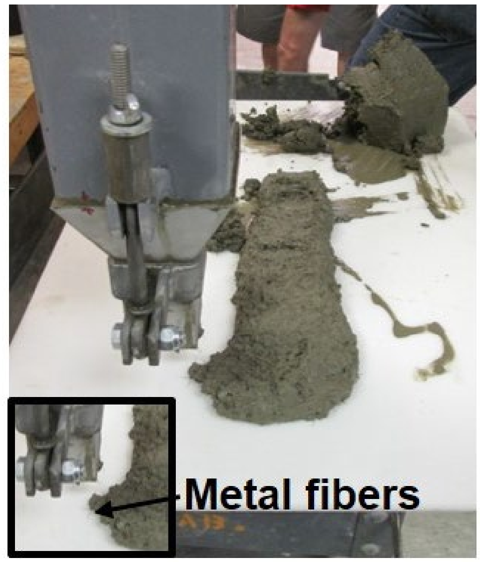
1. **Mix 1 extruder test. Final w/c = 0.47.**  **MIX 1 BASELINE**[1]	2. **Mix 2 extruder test following mixing. Material extruded well with some tearing.**  **MIX 2 TYPE III CEMENT**[2]

Figure 3-18 (Cont'd).

3. Mix 3 initial extruder test. The material clogged at the base of the barrel and within the nozzle. Notice where the nozzle attaches to the barrel base the bleed water that squeezes out when the drive handle is lowered.

MIX 3 METAL FIBERS[3]

4. Mix 3 Extruder test after extra water was added to the test mix. The inset shows the metal fibers protruding from the material.

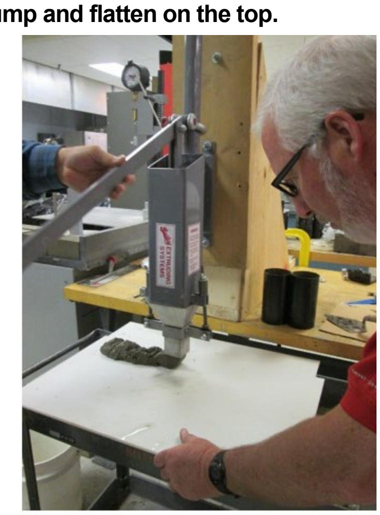


MIX 3 METAL FIBERS[4]

5. Mix 5 the material extruded fine, followed by bleed water coming through the seam between the barrel and the nozzle, then the nozzle clogged. Similar to the metal fibers, the polypropylene fibers protruded out of the mixture.

MIX 5 POLY FIBERS[5]

6. Mix 6 extrusion test for fly ash. The material extruded with minimal load needed on the handle. The shape of the bead tended to slump and flatten on the top.



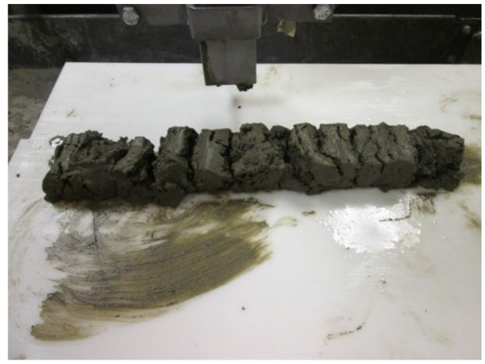
MIX 6 FLY ASH[6]

Figure 3-18 (Cont'd).

7. Mix 7 extrusion test after completion of mixing.

MIX 7 BENTONITE[7]

8. Mix 7 extra water added and the extrusion test was re-run.



MIX 7 BENTONITE[8]

9. Mix 8 extruder test following mixing. The material clogged in the barrel and nozzle. The initial w/c started lower at 0.39 as this is chemical admixture is a hrWR.

MIX 8 HRWR[9]

10. Mix 8 extruder test following extra water added. Final w/c = 0.41. The extra water improved the extrusion.

MIX 8 HRWR[10]

11. Mix 12 satisfactory extrusion of material. Final w/c of test mix was 0.41.

MIX 12 FRWR[11]

12. Extrusion test for Mixtures 9 Silica fume, 10 Accelerator, and 11 Shrinkage Reducer.

No photograph available

3.4.2 Slump and flow table tests

Table 3-3 lists the measured slump values for each test mixture. For comparison, Figure 3-19 shows all of the slump measurements in relation to Mix 1 Baseline. Overall, changing the cement type and the use of chemical admixtures had the least impact on the slump readings, this being a change in the slump of less than 1 in. The measured slump with the Type III cement (Mix 2) resulted in a slightly stiffer mix, reducing the slump by 0.75 in. compared to the baseline mix. This is likely due to the finer particles in Type III cement influencing the water demand as the water/cement ratio remained unchanged at 0.47. Adjusting the mix water might create a comparable slump. For comparison, Figures 3-20 and 3-21, respectively, show the measured slump of each mixture relative to its water-cement ratio, and flow table (%) relative to the measured slump.

The slump change for the four mixtures using chemical admixtures was ±1 in. compared to the baseline mix. The addition of the FRWR (Mix 12) had almost no change on the slump compared to the Baseline. There was a slight slump loss of 0.75 in. with the high-range water reducer (Mix 8). Since the liquid admixtures are water-based, the quantity of water contributed by the admixture was calculated and the total amount of mix water reduced. To account for the change in slump readings, the quantity of water contributed by the admixture was calculated and the total mix water reduced. Mix 10 with the accelerator was more fluid, while Mix 11 with the shrinkage reducer was slightly stiffer. A further observation regarding workability as measured by the slump test is that the effect of chemical admixtures to the baseline mixture was not excessive, suggesting that these mixtures could be further optimized by adjusting the admixture dosages and/or the water content.

The two mixtures that included fibers resulted in stiffer mixtures and reduced slump. Mix 3 with metal fibers resulted in a measured slump of 0.5 in.; while Mix 5 with the polypropylene fibers lost 1.25 in. with a slump reading of 1.5 in. The w/c of both mixes at the time of the slump test was 0.47. For Mix 3, the extrusion test at this w/c was not successful and additional water was added to the mix for a final w/c of 0.48. It was not measured, but it is likely that the slump at the higher w/c would have been slightly higher. No additional water was added to Mix 5.

Perhaps the most significant effect on slump came from the additions of fly ash, silica fume, and bentonite. The additions of 5% bentonite based on cement content (Mix 7) and the silica fume at 10% cement replacement (Mix 9) resulted in stiffer mixtures, with slump values of 0.50 in. and 0 in. for bentonite and silica fume, respectively. Adjustments to the mix water would likely be needed. In the case of the silica fume with no change in slump, the utility of this test would seem uncertain. Conversely, but not unexpectedly, the mixture replacing 20% of the cement content with fly ash (Mix 6) was much more fluid as the slump increased more than twice that of the baseline mix to almost 7 in. and the flow table measurements also increased. This was the highest slump reading of all the test mixtures. Care will be needed using fly ash as a single additive as a material this fluid may not be suitable for additive construction printing application.

The two mixtures that were most similar to the Mix 1 Baseline were Mix 3 Type III Cement and Mix 10 Accelerator. There were slight changes to the slump for Mixes 3 and 10 being reduced and increased, respectively. Yet for both mixes the flow stayed similar to that of Mix 1.

The slump measurement for the shrinkage-reducing admixture (Mix 11) and FRWR (Mix 12) were comparable to the baseline mix; however, the flow was reduced for both mixtures.

The concrete pumping industry and researchers focused on printing concrete are moving toward determining the rheology of fresh concrete (Le et al. 2012a; Ferraris, de Larrard, and Martys 2001). Characteristics such as the material's yield stress and plastic viscosity are needed to describe the rheology of a mixture; however, neither of these is quantified using either the slump test or the flow table test, where the slump test measures consistency and both the slump and flow table tests only provide an indication of the yield stress, according to Struble (2006). Ferraris and de Larrard (1998) proposed a modified slump test to measure both yield stress and plastic viscosity. The procedure uses the standard slump cone along with a vertical rod and a sliding disk to measure the time needed for the material to reach a 4 in slump (Ferraris and de Larrard 1998). Additionally, the use of more refined techniques such as rheometers has gained popularity for characterizing pumping concretes (Jolin et al. 2009) and printing concretes (Le et al. 2012a). This approach might be considered for application to additive construction.

Table 3-3. Measured slump and average flow table readings for laboratory test mixtures. The bold font indicates the test mixtures with the lowest slump and flow table readings.

Mix ID	Mix Name	Measured Slump (in.)	Average Flow (%)
1	Baseline	2.75	105.3
2	Type III cement	2.0	108.1
3	**Baseline + Metal fibers**	**0.5**	**45.4**
5	Baseline + Polypropylene fibers	1.5	77.2
6	Baseline + Fly Ash	6.75	122.3
7	**Baseline + Bentonite**	**0.5**	**57.0**
8	Baseline + High-range water reducer	2.0	70.0
9	**Baseline + Silica fume**	**0.0**	**64.5**
10	Baseline + Accelerator 60 fl oz/cwt	3.5	101.0
11	Baseline + Shrinkage Reducer	2.25	87.8
12	Baseline + FRWR	3.0	73.0

Figure 3-19. Measured slump comparison of laboratory test mixtures to the Baseline mixture (Mix 1). The red dotted line extends the slump of the baseline mixture to compare the other mixtures.

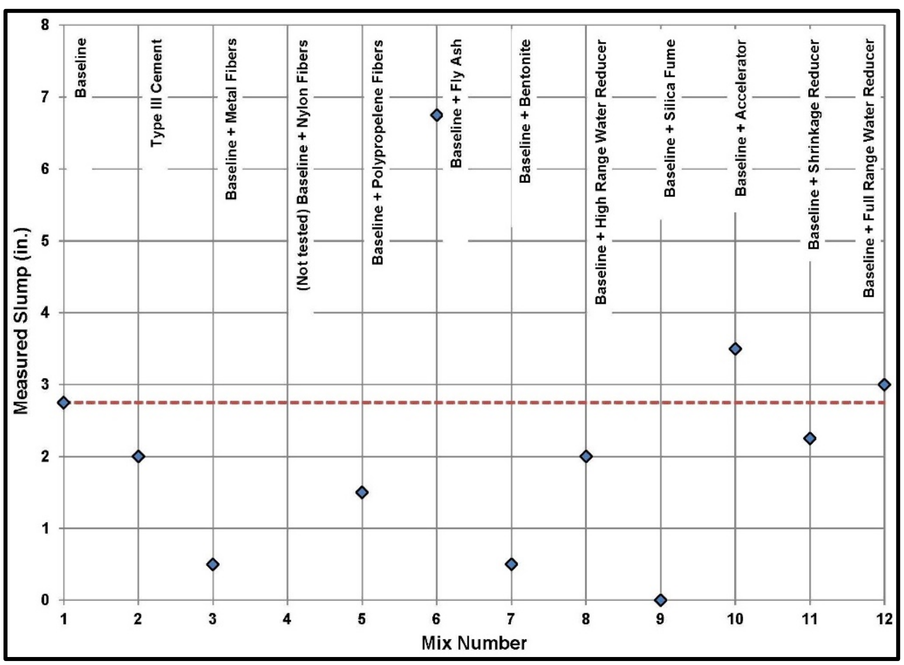


Figure 3-20. Comparison of slump to mixture water-cement ratio.

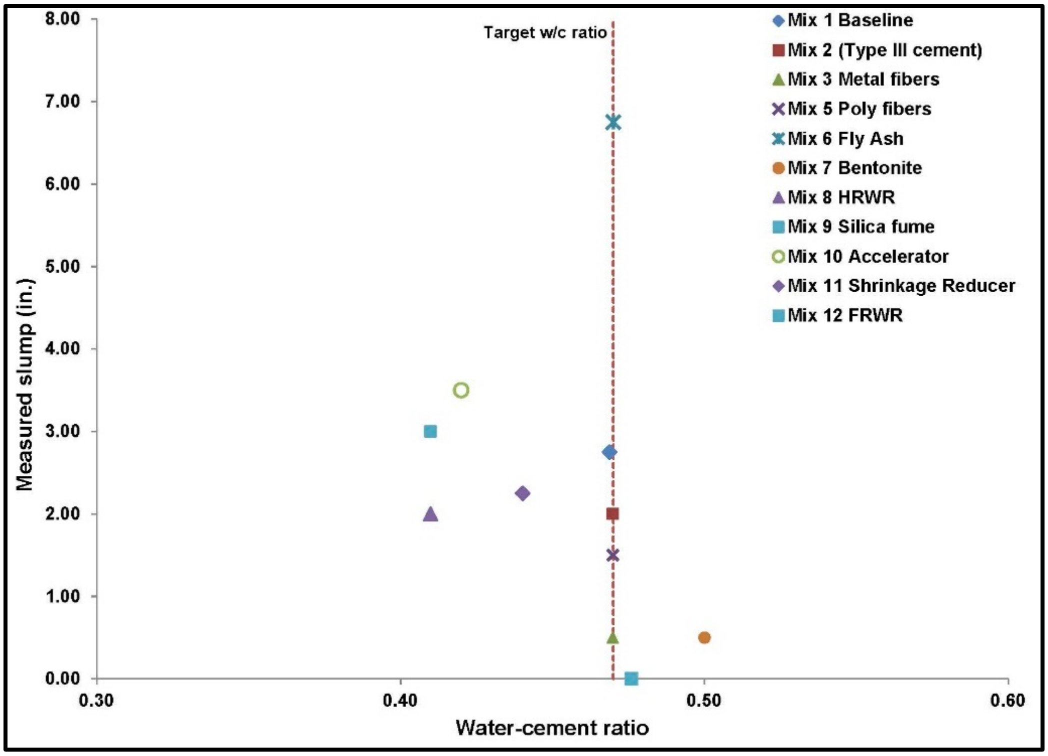
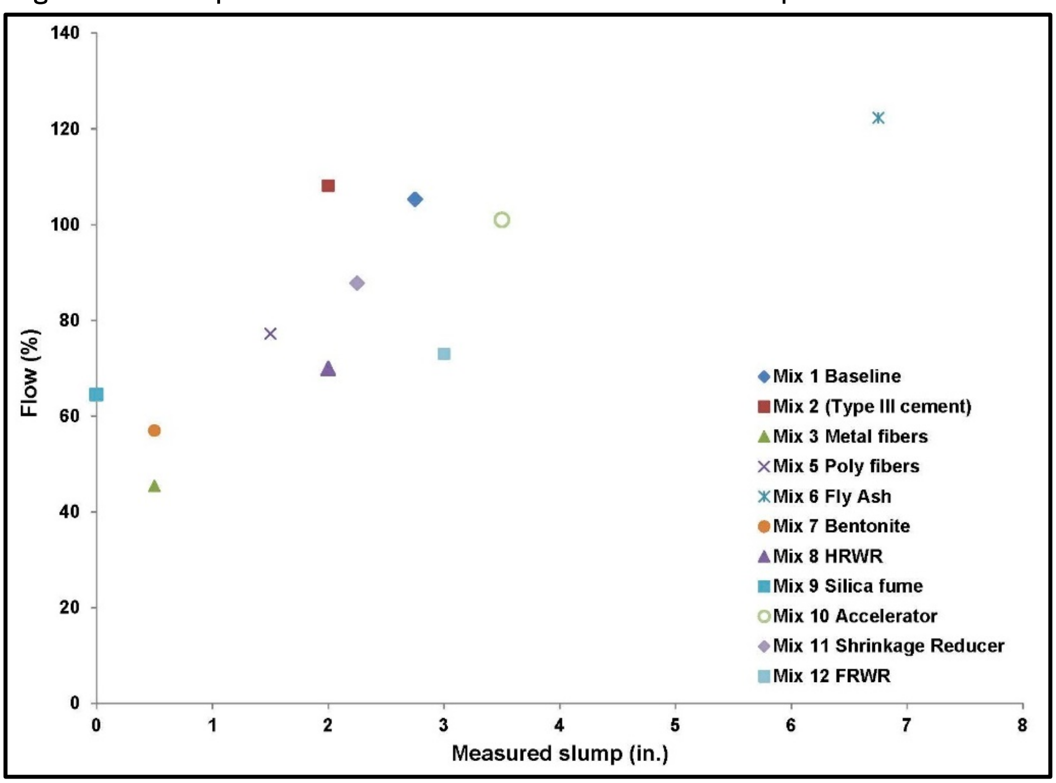


Figure 3-21. Comparison of flow table results to the measured slump for each test mixture.



3.4.3 Time of set

Table 3-4 lists the setting times. Mix 1 reached initial set at 3 hrs, 30 min and final set at 5 hrs, 17 min. There were two mixtures that reached initial set in less time than the baseline mix: Mix 10 Accelerator, which was approximately 60 min faster, and Mix 3 Metal Fibers. The initial set time for Mix 7 Bentonite was similar to the Baseline mix at 3 hrs, 22 min. Mix 5 Poly Fibers reached initial set approximately 10 min after the Baseline. Interestingly, Mix 2 with Type III Cement reached initial set after 4 hrs. Not surprisingly, the mix containing Fly Ash (Mix 6) required the greatest amount of time to reach both initial and final set at 5 hrs, 7 min and 7 hrs, 18 min, respectively.

Table 3-4. Summary of initial and final setting times of test mixtures.

Mix Number	Mix Name	Initial Set (hr:mm)	Final Set (hr:mm)
1	Baseline	3:19	5:17
2	Type III cement	4:07	6:53
3	Baseline + Metal Fibers	3:10	7:03
5	Baseliine + Polypropelene Fibers	3:41	5:47
6	Baseline + Fly Ash	5:07	7:18
7	Baseline + Bentonite	3:22	6:11
8	Baseline + High Range Water Reducer	4:13	6:00
9	Baseline + Silica Fume	4:00	5:30
10	Baseline + Acceleratore 60 fl oz/cwt	2:26	3:43
11	Baseline + Shrinkage Reducer	4:11	6:00
12	Baseline + Full Range Water Reducer	4:00	5:10

The Baseline mix reached final set in 5 hrs, 17 min. Mix 10 reached final set after 3 hrs, 43 min, or 78 min after initial set. The next mix to reach final set in less time than the Baseline was Mix 12 FRWR at 5 hrs, 10 min. Figures 3-22 through 3-26 show tested samples.

Figure 3-22. Mix 2 Type III cement set time test specimen.

Figure 3-23. Mix 3 Metal Fibers set time test specimen.

Figure 3-24. Mix 8 hrWR set time test specimen.

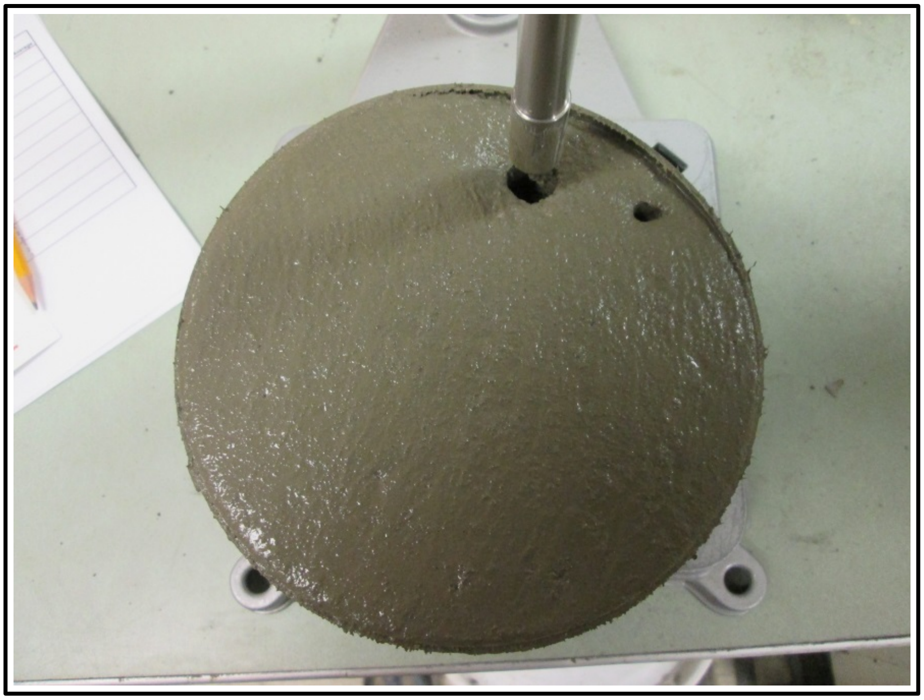


Figure 3-25. Mix 9 Silica Fume set time test specimen.

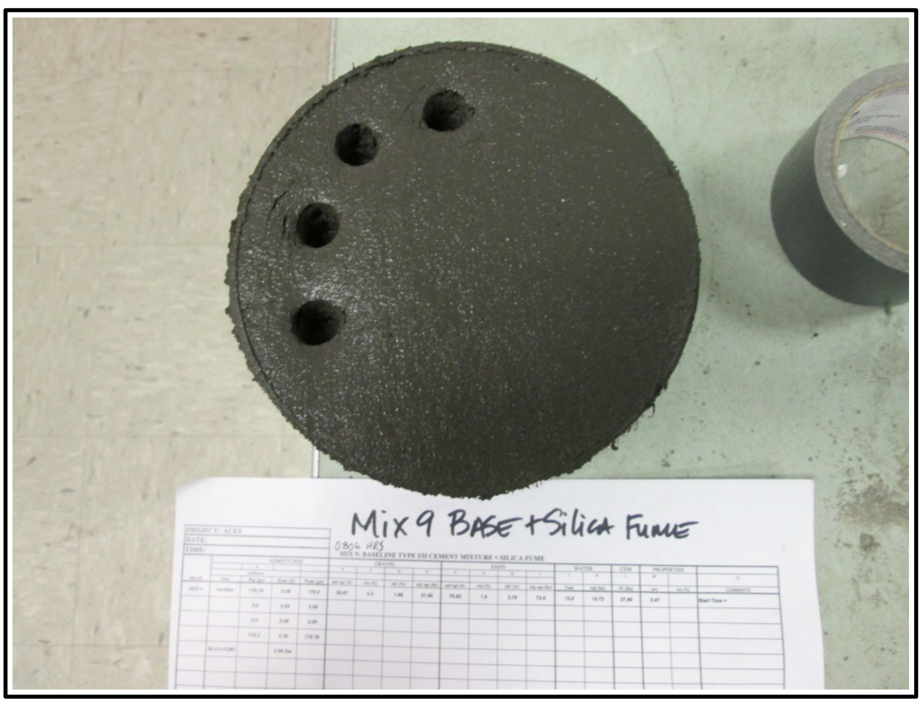


Figure 3-26. Mix 12 FRWR set time test specimen.

3.5 Hardened properties

3.5.1 Compression strength

Table 3-5 summarizes the average compressive strengths for each mix and test age. The mode of failure during the compressive strength testing was consistent, i.e., the cubes were crushed into small pieces. Except where noted, the average value was generated from testing three cubes. The compressive strength for the Baseline mix starts at 74 psi at 4 hrs, and increases to 714, 3,465, 5,394, and 5,988 psi at 8, 24, and 168 hrs (7 days), and 672 hrs (28 days), respectively.

3.5.1.1 Early age (4, 8, and 24 hrs)

Figure 3-27 shows a plot for the average compressive strength (psi) versus age (hours) for early age tests at 4 hrs, 8 hrs, and 24 hrs. At both the 4- and 8-hr ages, Mix 10 Accelerator was the only mix with average compressive strengths that exceeded the Baseline mix, well surpassing the Baseline by 1.5 times. The strengths for Mix 10 at 4- and 8-hr test ages were 167 and 1,149 psi, respectively. Conversely, both Mix 6 Fly Ash and Mix 9 Silica Fume performed the worst with strength results below the baseline strength at 31 psi after 4 hrs.

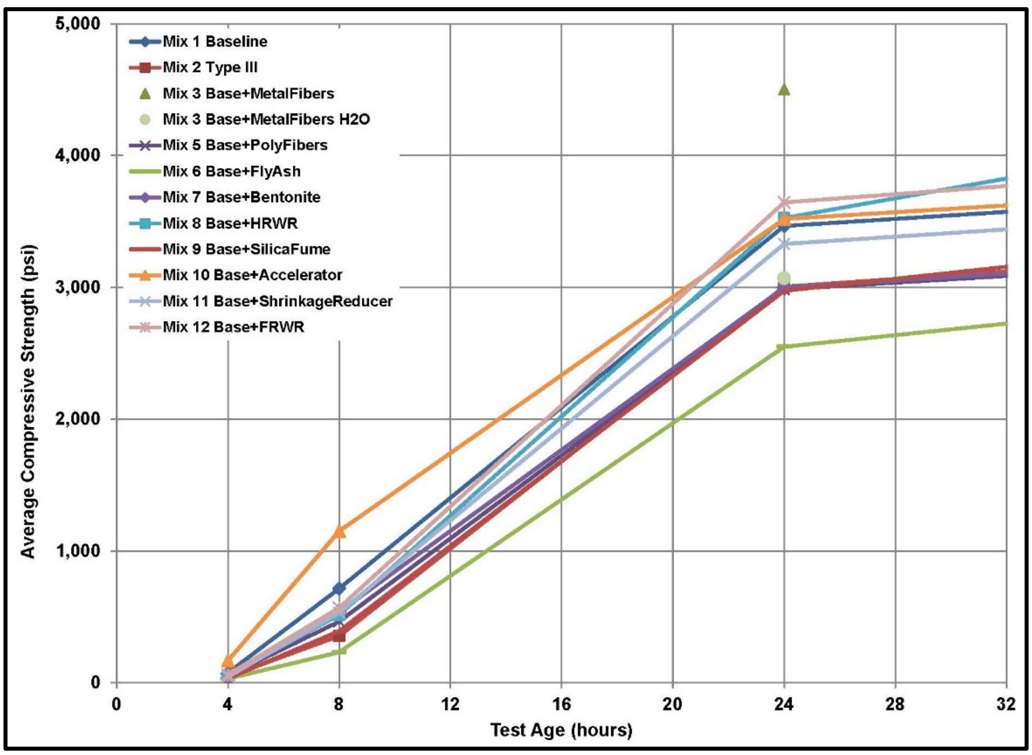
Table 3-5. Summary of average compressive strength.

Mix Number	Mix Name	Average Compressive Strength (psi) Test Age (hours) 4	8	24	168	672
1	Baseline	74	714	3,465	5,394	5,988
2	Type III cement	45	355	3,004	5,109[A]	5,252[B]
3	Baseline + Metal fibers[C]	Note[E]	Note[E]	4,501[A]	Note[E]	Note[E]
3	Baseline + Metal fibers (after water)[D]	Note[E]	Note[E]	3,068[A]	Note[E]	Note[E]
5	Baseline + Polypropelene fibers	53	464	2,984	4,819	4,787[F]
6	Baseline + Fly Ash	31	231	2,549	5,713	6,341
7	Baseline + Bentonite	69	536	2,996[A]	4,908[A]	4,569[A,F]
8	Baseline + High range water reducer	54	515	3,525	5,169[A]	5,219[B]
9	Baseline + Silica fume	31	391	2,973	6,255[A]	6,787
10	Baseline + Accelerator 60 fl oz/cwt	167	1,149	3,518	5,380[A]	6,390[A]
11	Baseline + Shrinkage reducer	45	532	3,329	5,325[A]	5,988
12	Baseline + Full range water reducer	60	568	3,644	5,884	5,690[A]

Table Notes:

- A Test result average of two cube specimens
- B Test result of one cube specimen
- C Following the addition of metal fibers, Mix 3 was very stiff.
- D Additional water was added to Mix 3 to improve the flow.
- E Not fabricated. Due to the stiffness of the mixture and difficulty of consolidation, 3 cubes were fabricated from the mixture before and after the added water for a total of 6 cubes. The cubes were tested only at a test age of 24 hr.
- F Average of three cubes where the strength of one cube was lower

Figure 3-27. Average compressive strength for early age test cubes.



At 8 hrs, compared to Mix 10, the next best mix was Mix 12 FRWR at 568 psi and Mix 7 Bentonite at 536 psi, both only reaching 80 and 75% of the strength of the Baseline mix, respectively. The three mixes with the lowest average compressive strengths were Mix 6 Fly Ash at 231 psi, Mix 2 Type III Cement at 355 psi, and Mix 9 Silica Fume at 391 psi.

At 24 hrs, the average compressive strengths for Mix 12 FRWR, Mix 8 hrWR, and Mix 10 Accelerator were greater than the baseline strength at 3,644, 3,525, and 3,518 psi, respectively. Mix 3 Metal Fibers before the additional water was added well exceeded the Baseline strength with 4,501 psi. Conversely, the 24-hr Mix 3 cubes tested after the water addition showed a decrease in the average compressive strength at 3,068 psi. The compressive strength for Mix 11 Base + Shrinkage Reducer was slightly less than that of the baseline at 3,329 psi. The mix with the lowest strength at 24 hrs continued to be Mix 6 Baseline + Fly Ash at 2,549 psi.

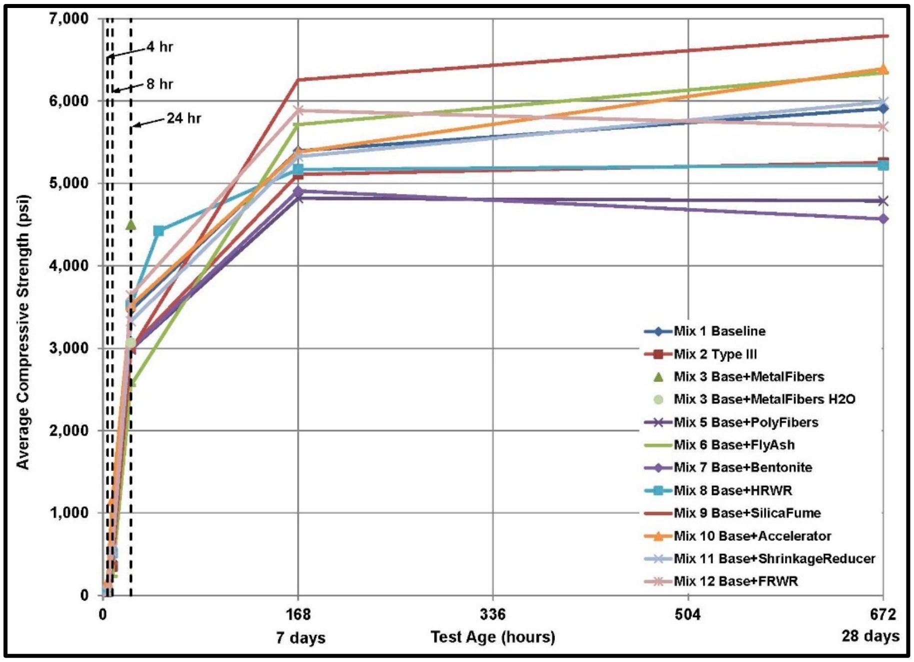
3.5.1.2 Hardened aged (7 and 28 days)

At 168 hrs (7 days) Mix 9 Silica Fume, Mix 12 FRWR, and Mix 6 Fly Ash all were above the Baseline strength at 6,255, 5,884, and 5,713 psi, respectively. Mix 10 Accelerator and Mix 11 Shrinkage Reducer were both slightly less than the baseline with compressive strengths of 5,380 and 5,325 psi, respectively. The lowest compressive strengths were Mix 5 PP (polypropylene fibers) at 4,819 psi, Mix 7 Bentonite at 4,908 psi, and Mix 2 Type III Cement at 5,109 psi.

At 672 hrs (28 days), Mix 9 Baseline + Silica Fume, Mix 10 Baseline + Accelerator, and Mix 6 were above the baseline strength at 6,787, 6,390, and 6,341 psi, respectively. Mix 11 Baseline + Shrinkage Reducer was the same as the Baseline strength at 5,988 psi, and Mix 12 was just below that at 5,690 psi. The lowest strengths were 4,569, 4,787, and 5,219 psi for Mixes 7, 5, and 8, respectively. Figure 3-28 shows the average compressive strength for all test mixtures at all test ages.

The effect of cement type on the compressive strength was clear. Mix 2 Type III Cement underperformed compared to the baseline. It was anticipated that the Type III cement would provide higher early strength; however, this was not the case.

Figure 3-28. Average compressive strength for aged test cubes.



At early ages, mixes with SCMs (silica fume and fly ash) performed poorly; however, at later ages the compressive strength improved significantly and performed better than the baseline. This is most likely due to the delayed pozzolanic reaction.

The inclusion of fibers in Mix 3 Metal Fibers and Mix 5 PP yielded compressive strength considerably higher than that of the mix with the metal fibers at a test age of 24 hrs. This mix was quite stiff and may not be suitable for additive construction, especially if the fibers should tend to clog in the delivery system. However, the information from Mix 3 is very limited and it is difficult to draw clear conclusions. The polypropylene fibers did not show an overall compressive strength benefit when compared to the baseline mix where the strengths were consistently lower than the baseline mix at all test ages. The compressive strength remained unchanged at 7 and 28 days.

Compressive strengths with Mix 7 Bentonite were consistently lower than the baseline throughout the testing. The 28-day strength for Mix 7 decreased compared to the 7-day strength. Testing notes indicated that the cubes at 28 days did not consolidate well during fabrication. There may have been voids present that reduced the overall strength.

For the mixtures with chemical admixtures, the accelerating admixture (Mix 10) performed well compared to the baseline at all test ages. The strengths with Mix 10 significantly exceeded that of the baseline mix at early ages, and also significantly increased the 28-day strength. The mixtures containing the other admixtures (HRWR, FRWR, and Shrinkage Reducer) were slower to gain strength at early ages compared to the baseline. The mixture with the Shrinkage Reducer (Mix 11) ended with a similar compressive strength as the baseline at 28 days. This may suggest that the shrinkage reducer does not impair the mix if there is a benefit to reducing shrinkage of the mixture.

Based on the compressive strength test results, the chemical admixtures that showed benefit were the accelerator and the FRWR. The inclusion of SCMs showed benefit, and both fly ash and silica fume advanced to the next round of testing. Concrete mixtures containing combinations of these four additives for further investigation include: accelerator/fly ash, accelerator/silica fume, accelerator/fly ash/silica fume, accelerator/FRWR, FRWR/fly ash, FRWR/silica fume, and FRWR/fly ash/silica fume.

3.5.2 Flexural strength

Table 3-6 summarizes the average flexural strengths for each mix and test age. Except where noted, the average value was generated from testing three prisms. The compressive strength for the Baseline mix starts at 132 psi and increases to 408, 726, 775 psi at 8, 24, and 168 hrs (7 days), and 672 hrs (28 days), respectively.

3.5.2.1 Early age (4, 8, and 24 hrs)

The Mix 1 Baseline test beam at 4 hrs failed during pre-loading; therefore, there was no reading at this test age. Since this makes it difficult to directly compare the test results of the other mixes, it is clear from the other mixes that the flexural strengths were quite low. However, two mixes with high early strengths were Mix 10 Accelerator with the highest strength at 44 psi and Mix 1 with the fiber mesh at 19 psi (Figure 3-29). The fiber mesh showed a clear improvement to the flexural strength, particularly at this early age.

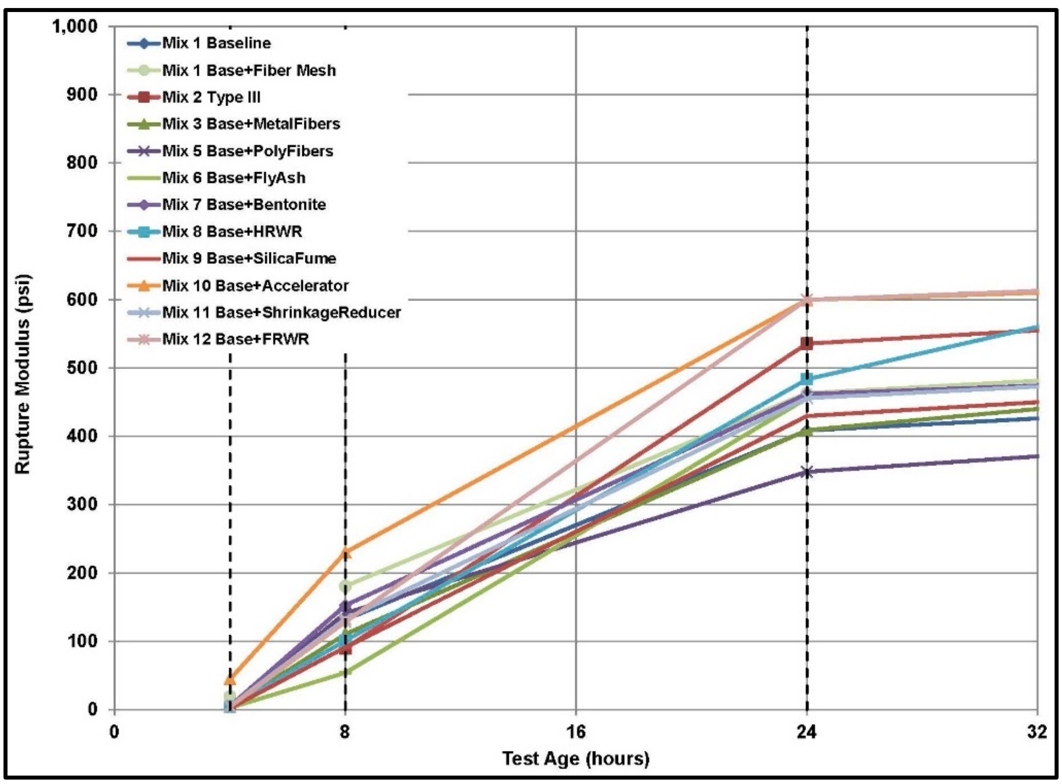
Table 3-6. Summary of flexural strength test beams.

Mix Number	Mix Name	Flexural Strength (psi) Test Age (hours) 4	8	24	168	672
1	Baseline	Note[A]	132	408	726	775
1 FM	Baseline + Fiber mesh	19	181	463	792	Note[B]
2	Type III cement	Note[A]	89	536	886	904
3	Baseline + Metal fibers[D]	4	110	409	967	851
5	Baseline + Polypropelene fibers	5	141	348	755	768
6	Baseline + Fly Ash	3	54	456	Note[C]	862
7	Baseline + Bentonite	5	153	462	688	743
8	Baseline + High range water reducer	4[E]	101	483	714[F]	Note[B]
9	Baseline + Silica fume	2	91	430	794	547
10	Baseline + Accelerator 60 fl oz/cwt	44	230	600	787	851
11	Baseline + Shrinkage reducer	5	133	456	760	815
12	Baseline + Full range water reducer	4	128	600	833	865

Table Notes:

- A Test beam failed either before or during pre-loading
- B Not tested
- C Beam tested, data file missing
- D Test beams fabricated before additional mix water added
- E Initial test beam failed during pre-loading
- F Test age at unscheduled 48hr

Figure 3-29. Early age flexural strength for single test beams.



At a test age of 8 hrs, the flexural strength of the Baseline mix was in the middle of all of the test mixtures. Both Mix 10 and Mix 1 with fiber mesh continued to show the highest flexural strengths at 230 and 181 psi, respectively. Mix 7 Bentonite showed a great increase in flexural strength at this early age at 153 psi. Mix 5 PP at 141 psi and Mix 11 Shrinkage Reducer at 133 psi were also within a similar strength range as the Baseline mix (132 psi). The mixes with the lowest flexural strengths were Mix 6 Fly Ash at 54 psi, Mix 2 Type III Cement at 89 psi, and Mix 9 Silica Fume at 91 psi.

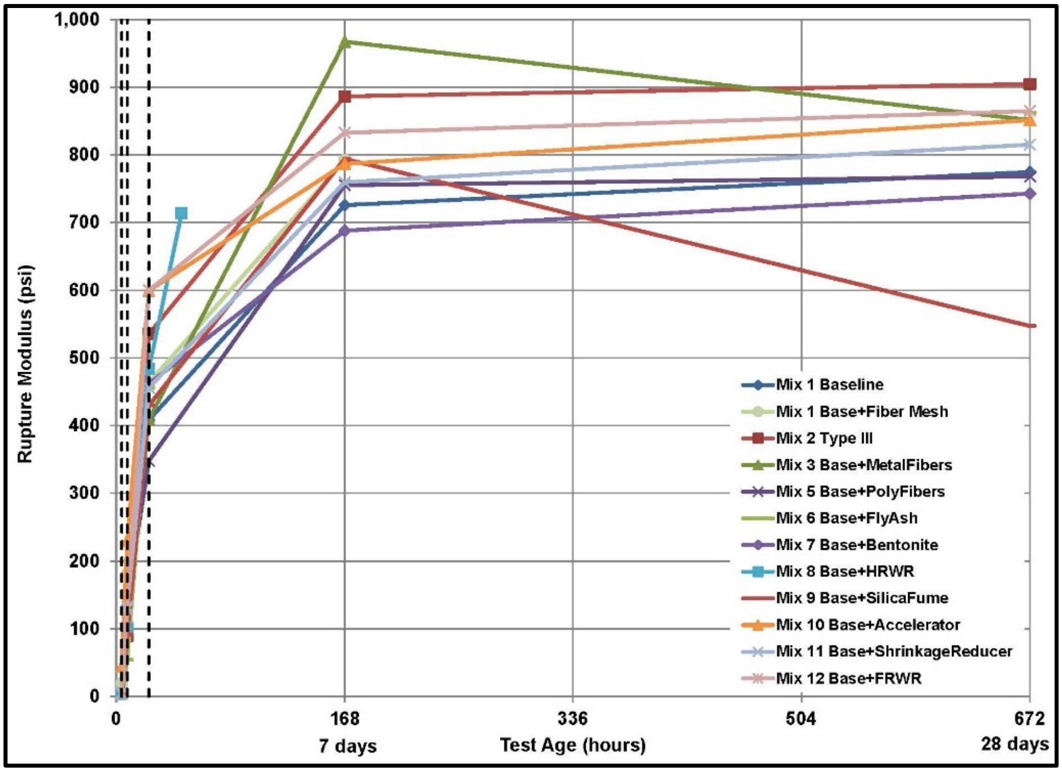
The flexural strengths at 24 hrs indicated that all of the test mixes, with the exception of Mix 5 PP at 348 psi, performed similarly or better than the Baseline mix. The flexural strength of the Baseline mix was 408 psi. The mixes with the highest flexural strengths were Mix 12 FRWR at 600 psi, Mix 10 Accelerator at 600 psi, and Mix 2 Type III Cement at 536 psi.

3.5.2.2 Hardened aged (7 and 28 days)

At 7 days, the test mixtures with flexural strengths with the highest flexural strengths, even exceeding the Baseline mix with the fiber mesh, were Mix 3 Metal Fibersat 967 psi, Mix 2 Type III Cement at 886 psi, and Mix 12 FRWR at 833 psi (Figure 3-30). Both Mix 1 with fiber mesh and Mix 10 had flexural strengths 10% greater than the Mix 1 Baseline of 726 psi. The only additive with a flexural strength lower than the Mix 1 Baseline was Mix 7, with the lowest flexural strength that was 5% lower at 688 psi. A testing note on Mix 8 hrWR was that the test beam was inadvertently tested at an earlier age of 48 hrs. This was the last test age for Mix 8.

At 28 days, Mix 1 Baseline had a flexural strength of 775 psi. There was no corresponding Baseline test beam with the fiber mesh at this test age. Still, the flexural strengths for Mix 2 Type III Cement and Mix 6 Fly Ash performed the best of the additives at 904 and 865 psi, respectively. Of the chemical admixtures, the Mix 10 Accelerator and the Mix 11 Shrinkage Reducer also performed better than the Baseline mix. Of the two test mixes that incorporated fibers, the metal fibers in Mix 3 performed better than the polypropylene fibers, with the strength of the polypropylene fibers slightly less than that of the Baseline mix at 768 psi. Mix 9 Silica Fume had the lowest 28-day flexural strength at 547 psi, well below the Baseline mix. The 28-day flexural strengths for both Mixes 9 and 3 decreased from the 7-day strength value. Mix 3 decreased by 12% and Mix 9 by 23%. The reason for this decrease is unclear, and no testing irregularities were noted.

Figure 3-30. Aged flexural strength for single test beams.



The flexural strength test results suggest that the flexural strength of the Baseline mix may be improved at early age with the addition of an accelerator. The Mix 12 FRWR was slower to gain strength at early age, but also at later ages outperformed the Baseline mix. The Mix 11 Shrinkage Reducer did not strongly influence the Baseline mix; however, it did not seem harmful either. The hrWR used in Mix 8 showed good flexural strength at 24 hrs, but otherwise the benefit was doubtful.

Regarding cement type, Mix 2 Type III Cement had slow strength gain at early age of 8 hrs, but then retained high flexural strength after that.

The addition of bentonite (Mix 7) showed some improvement compared to the Baseline at 8 hrs; however, bentonite did not show significant results. Similarly, with the addition of SCMs, neither the Silica Fume (Mix 9) nor the Fly Ash (Mix 6) improved the flexural strength at any test age.

Flexural strength with fibers showed a marked improvement with the Steel Fibers (Mix 3); however, Mix 5 with the Polypropylene Fibers exhibited only average flexural strength.

The trial of adding a fiber mesh showed strong promise, particularly at early age. The inclusion of fiber mesh should be tested further for its utility in additive construction.

It was unclear why Mix 3 and Mix 9 28-day strengths are lower.

3.5.3 Splitting tensile

Overall, the average splitting tensile strengths of all of the test mixtures were lower than the flexural strengths (modulus of rupture) of corresponding mixes, and much lower than the compressive strengths (Table 3-7). This is consistent with the literature (Mindess, Young, and Darwin 2003).

Table 3-7. Summary of average splitting tensile strengths for the test mixtures.

Mix Number	Mix Name	Average Splitting Tensile Strength (psi) Test Age (hours)				
		4	8	24	168	672
1	Baseline	Note[A]	39	275	455	597
2	Type III cement	2	31	335	517	583
3	Baseline + Metal fibers (before water)	Note[B]	59	470	700	873
3	Baseline + Metal fibers (after water)	Note[C]	Note[C]	367	Note[C]	Note[C]
5	Baseline + Polypropelene fibers	4	48	288	503	559
6	Baseline + Fly Ash	1	23	272	458	610
7	Baseline + Bentonite	3	44	352	509	581
8	Baseline + High range water reducer	1	29	305	546	613
9	Baseline + Silica fume	1	39	247	524	675
10	Baseline + Accelerator 60 fl oz/cwt	13	105	336	531	568
11	Baseline + Shrinkage reducer	2	32	296	534	619
12	Baseline + Full range water reducer	2	34	357	545	589

Table Notes:
- A Test cylinder fell to pieces during demolding
- B Not tested
- C Not fabricated. Limited test cylinders fabricated.

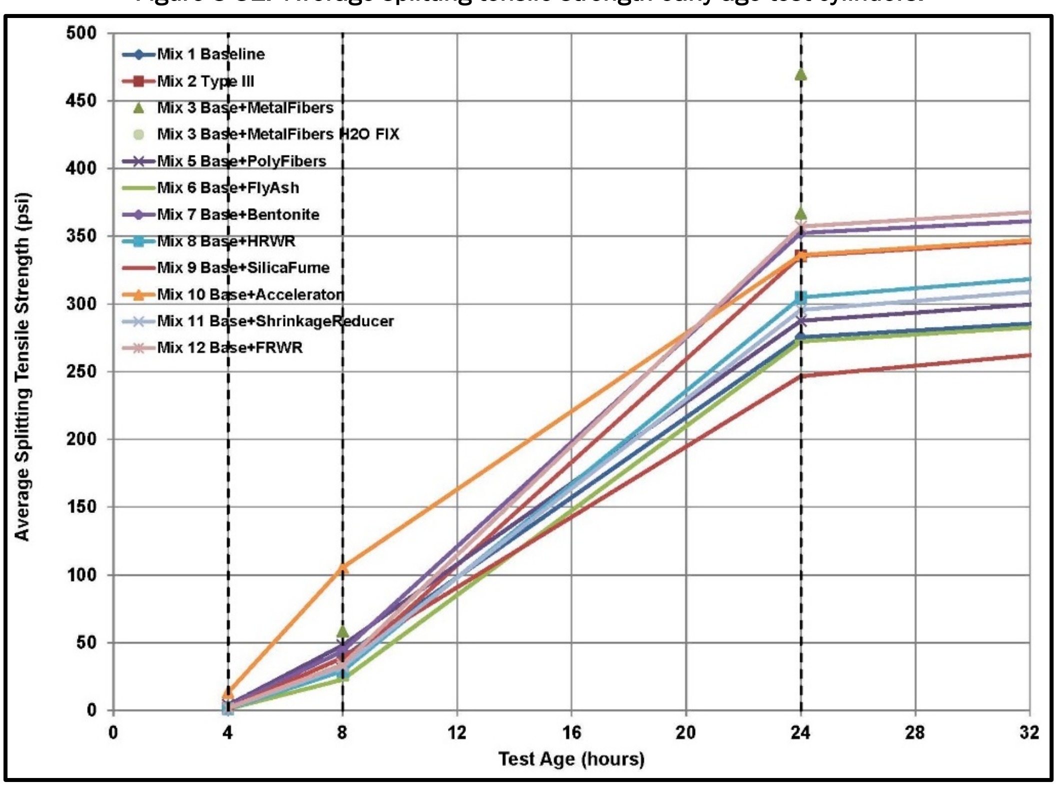
3.5.3.1 Early age (4, 8, and 24 hrs)

Figure 3-31 shows the average splitting tensile strength for the early test ages up to 24 hrs. As previously stated, there are no 4-hr splitting tensile strengths for the Mix 1 Baseline since the test cylinders were still too underdeveloped to remove from the plastic molds. This soft condition was similar for nearly all of the remaining test mixtures at the 4-hr test age, as indicated by the very low tensile strength values (Table 3-6). The mixtures with the lowest values were Mix 6 Fly Ash, Mix 8 hrWR, and Mix 9 Silica Fume. The exception to this was Mix 10 Accelerator with a comparatively very high average tensile strength at 13 psi. Clearly, the addition of the accelerator provided an early strength increase.

At a test age of 8 hrs, the average splitting tensile strength of the Baseline mix was 39 psi. Mix 9 Silica Fume has a similar strength. Test mixtures that performed better than the Baseline were Mix 10 Accelerator at 105 psi, which was more than 2 times the Baseline splitting tensile strength, (59 psi was the next highest strength from Mix 3 Metal Fibers), followed by Mix 5 PP at 48 psi. The mixtures that performed below the Baseline mix were Mix 6 Fly Ash, Mix 8 hrWR, and Mix 2 Type III Cement with strengths of 23, 29, and 31 psi, respectively.

At 24 hrs, the splitting tensile strength of nearly all of the test mixtures exceeded the Baseline mix (Figure 3-31). Mix 3 Metal Fibers clearly outperformed all of the other test mixtures, whether before (470 psi) or after the added water (367 psi) to the mixture. These strengths compared well to those of the Baseline mix, of 275 psi. The strength of Mix 10 Accelerator at 336 psi slowed compared to the other additives. The two mixtures with splitting tensile strengths less than the Baseline were Mix 9 Silica Fume at 247 psi and Mix 6 Fly Ash at 272 psi.

Figure 3-31. Average splitting tensile strength early age test cylinders.



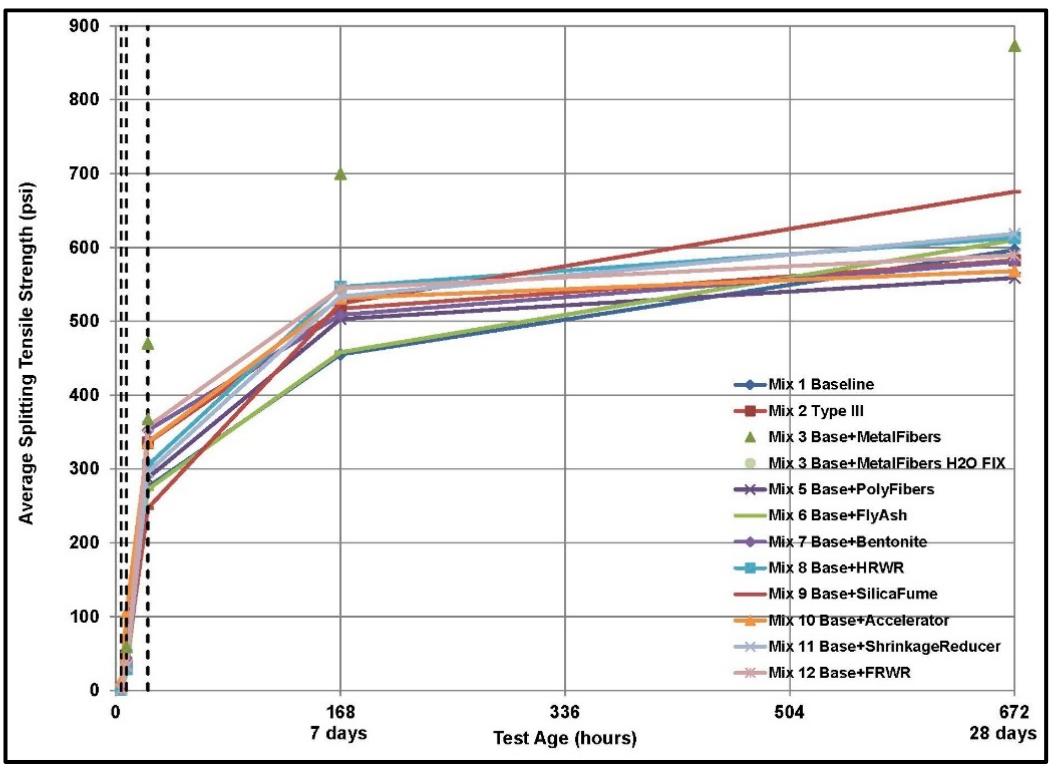
3.5.3.2 Hardened aged (7 and 28 days)

Interestingly, at 7 days, the splitting tensile strength of all of the test mixes outperformed the Baseline mixture (455 psi), including Mix 6 Fly Ash at 458 psi (Figure 3-32). The mixture exhibiting the best splitting tensile strength continued to be Mix 3 Metal Fibers followed by Mix 8 hrWR at 546 psi.

At 28 days, the mixtures that distinctly performed better than the Baseline (597 psi) were Mix 3 (873 psi) followed by Mix 9 Silica Fume at 675 psi, and Mix 11 Shrinkage Reducer at 619 psi. The splitting tensile strength of Mix 10 Accelerator at 568 psi ended slightly below the Baseline. The mix that performed below the Baseline was Mix 5 PP at 559 psi, which was approximately 7% lower.

At early age, the accelerator showed itself to be beneficial with strengths that well exceeded those of the Baseline mixture. There was a noticeable difference at the 24-hr test age where nearly all of the additives improved the splitting tensile strength of the test mix compared to the Baseline. The greatest improvement was with the metal fibers for all of the remaining test ages.

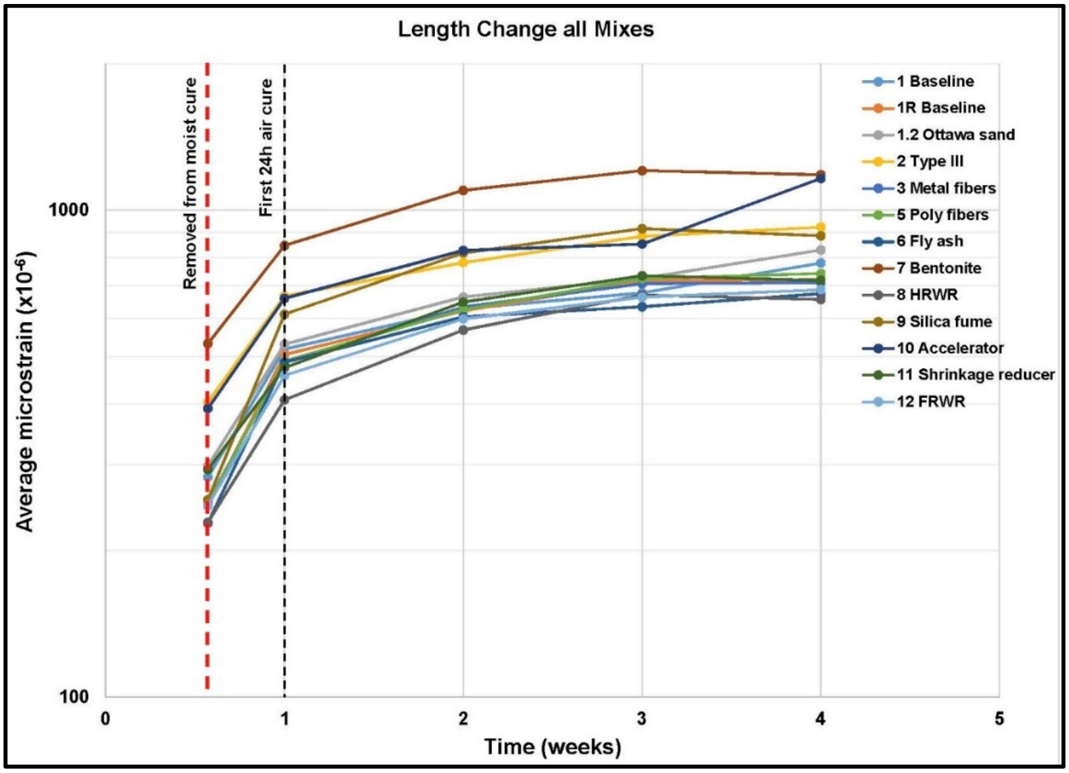
Figure 3-32. Average splitting tensile strength for aged test cylinders.



3.5.4 Drying shrinkage

Figure 3-33 summarizes the results of the drying shrinkage test. The results are the average shrinkage of the test specimens reported as microstrain.

Figure 3-33. Comparison of length change for all test mixtures.



Some observations of the results of the shrinkage testing are:

- All of the candidate test mixtures showed the highest drying shrinkage rate after removal from the curing box during the initial 24 hrs exposed to air. After the initial 24 hrs in air storage, the shrinkage rate trended in a more linear fashion for the remainder of the testing.
- Mix 7 Bentonite consistently showed the highest drying shrinkage rate throughout the testing.
- Mix 8 hrWR consistently showed the lowest drying shrinkage rate throughout the testing. Mix 6 Fly Ash also exhibited a low shrinkage rate throughout the testing.
- It is unclear why the shrinkage rate of Mix 10 Accelerator suddenly increased between Weeks 3 and 4.
- The Baseline mixes (Mix 1R and Mix 1.2) showed similar shrinkage, suggesting there is minimal effect from using different fine aggregate.

- The Baseline mixes (Mix 1R and Mix 1.2) showed similar shrinkage rates to those mixtures in the middle of all of the test mixtures, such as Mix 3 Metal Fibers, Mix 5 PP, and Mix 11 Shrinkage-Reducing Admixture.
- Mix 2 Type III Cement, Mix 9 Silica Fume, and Mix 10 Accelerator exhibited similar shrinkage rates; all were higher than the remaining mixes, but less than Mix 7 Bentonite.
- The three mixtures with the lowest drying shrinkage rate were Mix 6 Fly Ash, Mix 8 hrWR, and Mix 12 FRWR. These three mixtures performed better than Mix 1R Baseline.

3.6 Conclusions

The purpose of this laboratory testing was to develop a concrete mixture for trial use in an additive construction application. This initial laboratory testing generated an understanding of the necessary characteristics of a concrete mix for 3D printing. Both the plastic and hardened states of the test mixtures were characterized during the testing. The characteristics of the baseline (control) concrete mixture were compared to 11 other concrete mixtures that added a single additive to the baseline mixture. A variety of additives were used ranging from fibers, to chemical admixtures, to SCMs, to bentonite. Test methods followed accepted methods, with modifications as needed. The exception to this was the extrusion test. The following conclusions were drawn from this testing:

1. This initial laboratory testing successfully prepared the basis for test methods useful for additional performance testing to optimize the concrete mixture and to use as quality control/quality acceptance methods for other candidate mixtures.
2. At the completion of mixing, the concrete mixture is continually changing due to the interaction of cement, water, and additives, and also due to the time elapsed when the material enters the delivery system until it is extruded out of the nozzle. These test methods will be useful to further determine the material characteristics as the quantity of material is scaled up and uninterrupted material mixing/printing is introduced. Since additive construction is in the early developmental stages, additional modifications and new methods for mixture characterization will be likely be developed.
3. To address the capability of the additive construction concrete mixtures being sourced from local materials, additional mixtures should be mixed and tested using ingredients sourced from other locations.
4. Test methods focused on early age as represented by testing at ages 4, 8, and 24 hrs. Hardened properties at customary test ages of 7 and 28 days

were included in the testing matrix to provide insight into the longer duration performance.

5. Regarding the matrix of test mixtures, while initially planned, a test mixture that included nylon fibers (designated as Mix 4) was not tested. It is recommended that nylon fibers be evaluated and tested as an additive for concrete mixtures for additive construction.
6. In its current form, the extrusion test, the first test on a mixture to evaluate its flow characteristics, is qualitative only. Innovation is needed to quantitatively determine a concrete mixture's characteristics.
7. Similarly, while the slump and flow table tests are commonly used, it was difficult to relate the measurements from either test to the plastic state of the mixture. These tests should be re-evaluated for their suitability for additive construction.
8. Regarding the types of additives used in the test mixtures:
   a. Type III cement did not show an overall benefit when compared to Type I/II cement in the Baseline mixture, in particular as related to set time. Type III cement should not be considered for further study.
   b. Metal fibers improved the tensile strength of the material compared to the Baseline mixture. The test data were limited, however, and additional testing is advised. Overcoming the tendency for fibers to clog within the delivery system will be significant for the inclusion of fibers in the mixture. This will need to be weighed against the material benefit.
   c. The chemical admixtures in the plastic state, such as slump, performed similarly to the Baseline mix. Of the chemical admixtures, the Accelerator clearly showed benefit for a significantly set time, and early compressive and tensile strengths. It is recommended that an accelerating admixture be used in additional testing. Benefits derived from using a high-range water reducer, an FRWR, or a shrinkage reducer was not as pronounced. For set times, all three admixtures took longer than the Baseline mix. They performed either similarly or slightly below the Baseline in terms of strength gain. The effects of including these admixtures will become clearer over time, and merit further study.
   d. The addition of supplemental cementitious materials such as fly ash and silica fume resulted in slower setting times, impacted slump (fly ash increased slump, silica fume decreased slump), and gave mixed results related to strength. However, given that these materials aid as a cement replacement, both materials should be studied further to determine effective proportions to the concrete mixture.
   e. The addition of bentonite in the mixture appeared to provide some shape stability. In the plastic state, Mix 7 was stiffer with a lower slump

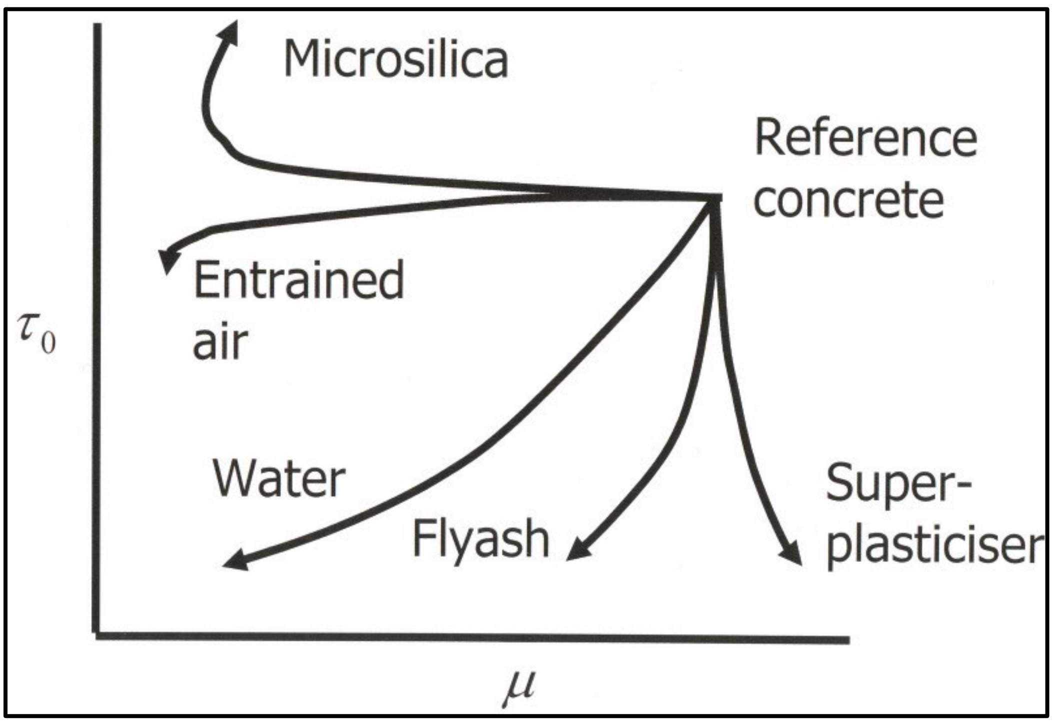
and flow compared to the Baseline mix. The initial set time was comparable to the Baseline and longer for final set. Generally, the strength properties of Mix 7 were lower than those of the Baseline. The 28-day compressive strength decreased. This may impact the long-term strength of mixtures containing bentonite; further study is needed. Optimizing the bentonite content to achieve the preferred characteristics would be worth additional study.

9. The next phase of material investigation needs to evaluate effective additive combinations and ingredient dosages for optimal concrete material properties. These mixture(s) need to be used in the delivery equipment system to better identify what works and what does not.

4 Rheology and Setting Quantification

The basic ingredients of ordinary portland cement concrete are coarse and fine aggregates, cement, and water. Admixture additions to this simple recipe can provide significant benefits in specific scenarios, especially with regard to rheology. Figure 4-1 illustrates typical effects on yield strength (τ_0, relates to force required to initiate flow) and the plastic viscosity coefficient (μ, relates to force required to increase flow) of classes of admixtures. Printable concrete should exhibit high static yield strength to hold its shape, low dynamic yield strength to aid pumping, and moderate plastic viscosity to avoid segregation of the aggregates. Since these goals oppose each other, engineers face several challenges when developing a suitable printing mixture.

Figure 4-1. Effects of admixture classes on rheological behavior.



The concrete mixture for ACES printing was developed after testing many possible admixture components (see earlier sections). The goal of those tests was to guide the design of a printable concrete mixture using only a small selection of the tested components. Instead, nearly all of the tested admixtures were used, resulting in a complicated mix with incompatible components and improper dosages that is highly sensitive to water content. In order of importance, the key issues facing the mixture design are

1. BASF states that "erratic slump behavior" may result from using FP 20 accelerator and naphthalene-based plasticizer together, which is observed in ACES mixes. The effects of the accelerator on initial and final set time have not been properly tested. Accelerator may not even be necessary for this mixture, depending on the speed of printing. This report should provide guidance for when to apply accelerator, and/or recommend changing to a polycarboxylate-based plasticizer.
2. Workability is currently adjusted by adding water at the time of mixing. This results in a higher w/c ratio and reduced strength. Only the minimum recommended dosage of superplasticizer is currently in use, so workability ought to be controlled by adding or removing superplasticizer instead of water.
3. Over double the manufacturer recommended dose of MasterMatrix 33 is currently in use following poorly reported bench testing to determine the dose. This component should be reduced or removed entirely, depending on rheology measurements and needs.
4. Aggregate gradation is poorly controlled. Major changes in rheology are possible with a uniform, well-graded, or gap-graded aggregate system.
5. The paste content relative to aggregates was only briefly tested in the previous report. Autogenous and drying shrinkage cracking are major problems that we have observed as a result of the high paste content. Major changes in rheology are also possible when adjusting the paste content of the mix.
6. At 3%wt of cement, bentonite may not be fully optimized. The previous report suggested additional testing to optimize the use of bentonite. As much as 10% replacement of cement has shown additional shrinkage reduction in the literature.
7. Better workability, strength gain, and long-term durability are possible if the silica fume content is increased to 10% of cement.
8. Better workability, durability, and long-term strength gain are possible if fly ash content is increased to 10%, or even 20%, of cement.

4.1 Purpose of each component

4.1.1 Mineral admixtures

Silica Fume. Highly pozzolanic with many hardened-state property improvements (strength, durability, etc.). Particles are much smaller than cement. At low to medium dose (5-10%wt replacement of cement), plastic viscosity is reduced. At high dose (15%wt replacement), yield strength may increase. Silica fume decreases set time, similar to (but not as strongly as) accelerator.

Fly Ash. Moderately pozzolanic, only contributes to late strength gain. Very low cost. Reduces both plastic viscosity and yield strength. Many Departments of Transportation (DOTs) currently specify at least 10%wt replacement of cement in all pavements.

Bentonite. Slightly pozzolanic. Prevents autogenous shrinkage and inhibits drying shrinkage by providing internal reservoirs of water after the concrete has hardened. Very small particles with a high water demand. May increase both yield strength and viscosity.

4.1.2 Chemical admixtures

Eucon 1037. High-range water reducer (superplasticizer), naphthalene sulfonate type. Low cost and globally available. Above the recommended dose, it can negatively affect hardened-state properties. Reduces yield strength and viscosity.

Glenium 7700. High-range water reducer (superplasticizer), polycarboxylate type. Not currently used in the ACES mix. More expensive than naphthalene type, but also more effective at lower doses. Better choice when using accelerator. Reduces yield strength and viscosity.

MasterMatrix 33. Improves response to vibration by reducing viscosity and/or dynamic yield strength. The manufacturer datasheet is not clear about what “rheology-controlling” means. The ACES mixture uses a lot of this component, but we have a poor understanding of its true effects.

MasterSet FP 20. Accelerator and mid-range plasticizer. A dose of 650mL per 100kg of cement will reduce initial set time (500psi penetration test) from 4.5 hours to 3.5 hours. At one point, the ACES mixture used nearly quadruple that dose, which can lead to the concrete setting while still in the pump.

4.2 Efficiency of testing

A large experimental matrix was originally designed to test each component at 0%, 50%, and 100% of current levels in full concrete batches during May, 2016 through June, 2016. Such tests require 3-5 people in the lab and occur at a slow rate of at most two mixes per day. Due to the lack of aggregate moisture correction and addition of water during mixing to achieve slump targets, many of the rheology results of this experiment are invalid.

The present report focuses on removing potential sources of variability. We will first investigate small batches of mortar with precise control over aggregate moisture content and water addition. Only one aggregate type with a well-controlled gradation will be used. Only 1-2 people are required in the lab and 6-12 batches per day are possible. Later testing will involve small batches of concrete.

4.3 Base mixture design

The base mortar and concrete mixtures were modeled based on the current ACES mixture design with a water to cementitious material ratio of 0.43, sand to cementitious material ratio of 2.25, and gravel to cementitious material ratio of 1 (See Table 4-1). Mortar batches were designed volumetrically to produce 1.8 L. Concrete batches were designed volumetrically to produce 18 L. Moisture corrections of -2% to +1% were applied to the fine aggregate as necessary. Moisture corrections of 0 to +1% were applied to the gravel as necessary.

Table 4-1. Component masses (in grams) in base mortar and concrete mixtures.

	Water	Cement	#100 Masonry Sand	#8 Fill Sand	3/8-in. Pea Gravel
Mortar	483	1123	2526.5	0	0
Concrete	3762	8748.5	19684	0	8748.5

4.4 Test plan

Mortar was mixed in a 5 qt. Hobart mixer according to ASTM C305 procedures. Initial tests on mortar included ASTM C1437 flow table measurements, ASTM C403 penetration tests, and subjective observations of segregation, bleeding, and "printability." Additional mixtures were batched to create cubes for ASTM C109 compressive strength testing at 1, 3, and 7 days of age. Compression specimens were cured in a box containing several wet towels, which has been shown in previous work to result in near 100% relative humidity inside the box. Then, 2x2 in. prisms were cast for drying shrinkage testing similar to ASTM C596, since we have observed shrinkage cracking on many elements printed at CERL. Specimens were cured in a box with wet towels for 7 days before exposure to laboratory conditions for drying. Finally, since a suitable small-scale rheometer vane could not be procured in a timely manner, the ICAR rheometer was used to test concrete containing gravel, which was manually mixed using a 4-in. rotary paddle in a 30-gal high density polyethylene (HDPE) drum. Refer to Table 4-2 for a description of admixtures tested in this report.

Table 4-2. Admixtures and doses tested in this report.

Admixture	Name	Units	Typical	Current	Tested
Accelerator	BASF FP 20	mL/100kg cm	500-1600	1020	204, 510, 1020, 2040
Navitas	BASF MasterMatrix 33	mL/100kg cm	130-780	1378	134, 345, 689, 1378
Superplasticizer	EUCON 1037	mL/100kg cm	520-1630	612	612, 1072, 1531
Shrinkage Reducer	BASF MasterLife SRA20	gal/yd^3	0.5-1.5	0	0.5, 1.0, 1.5
Bentonite	Halliburton AQUAGEL	%wt of cm	0.5-10	3	1.5, 3, 6
Class C Fly Ash	Boral Scherer Silo 3	%wt of cm	10-25	5	5, 10
Silica Fume	WRG Force 10000	%wt of cm	5-15	5	5, 10

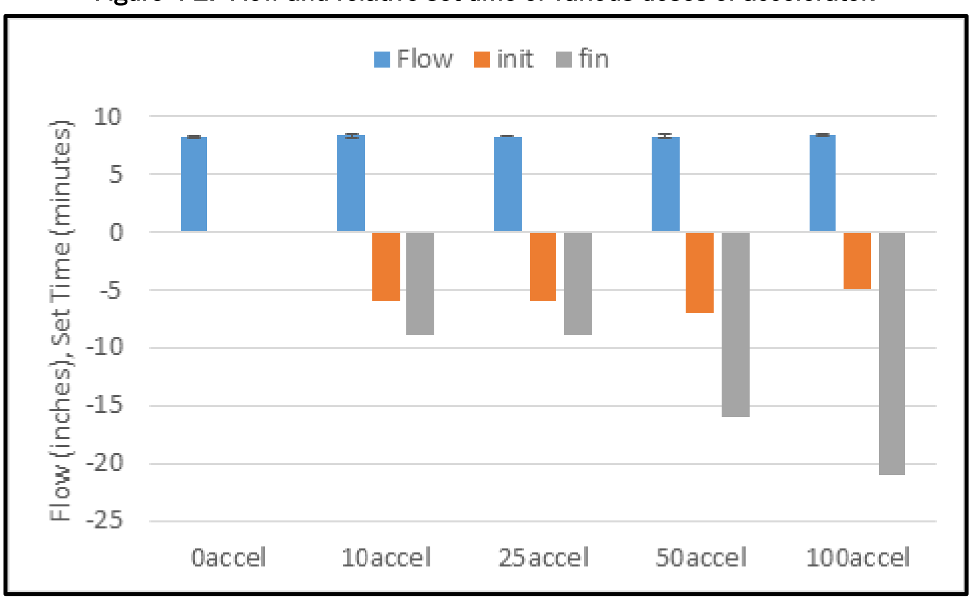
4.5 Flow table and set time by penetration resistance

Flow and penetration tests occurred on 5 separate days. To address variability due to aggregate moisture and laboratory conditions, a control mixture of plain base mortar was tested on each day alongside the mixtures containing admixtures. Initial (500 psi) and final (4000 psi) set time results below are reported relative to the daily control. A negative relative set time means set was accelerated, while a positive relative set time means set was retarded.

4.5.1 Effect of accelerator

The accelerator had a minimal positive effect on flow, just barely outside the deviation for the highest dose (Figure 4-2). Initial set was accelerated by 5-7 minutes for all doses. Final set showed the greatest effect with increasing dose, resulting in accelerations of 9, 16, and 21 minutes.

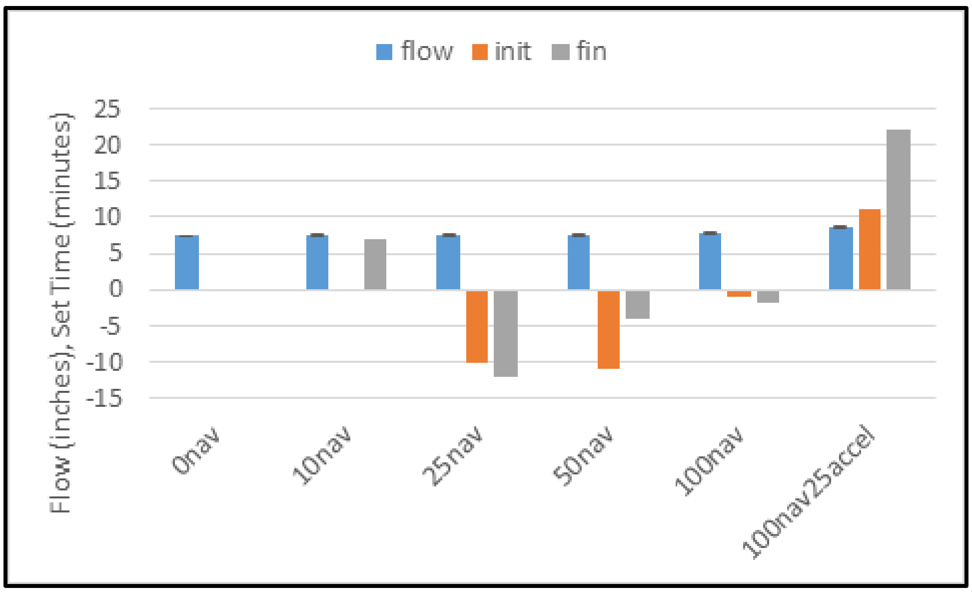
Figure 4-2. Flow and relative set time of various doses of accelerator.



4.5.2 Effect of Navitas

The Navitas (MasterMatrix 33) had a slight positive effect on flow, especially at higher doses. At doses within the manufacturer recommendation (25nav and 50nav in Figure 4-3), initial set was accelerated by about 10 minutes and final set was accelerated by 12 and 4 minutes. These results support the manufacturer claim that the admixture develops a secondary polymer network to aid early age shape stability. It should be noted that this behavior was only observed within the recommended dosage. When combining accelerator and Navitas, there is actually a significant retardation of set (11 minutes initial, 22 minutes final). Therefore, combining these two admixtures could result in unpredictable early age behavior in a concrete mixture. The next sub-section investigates combinations of these admixtures in detail.

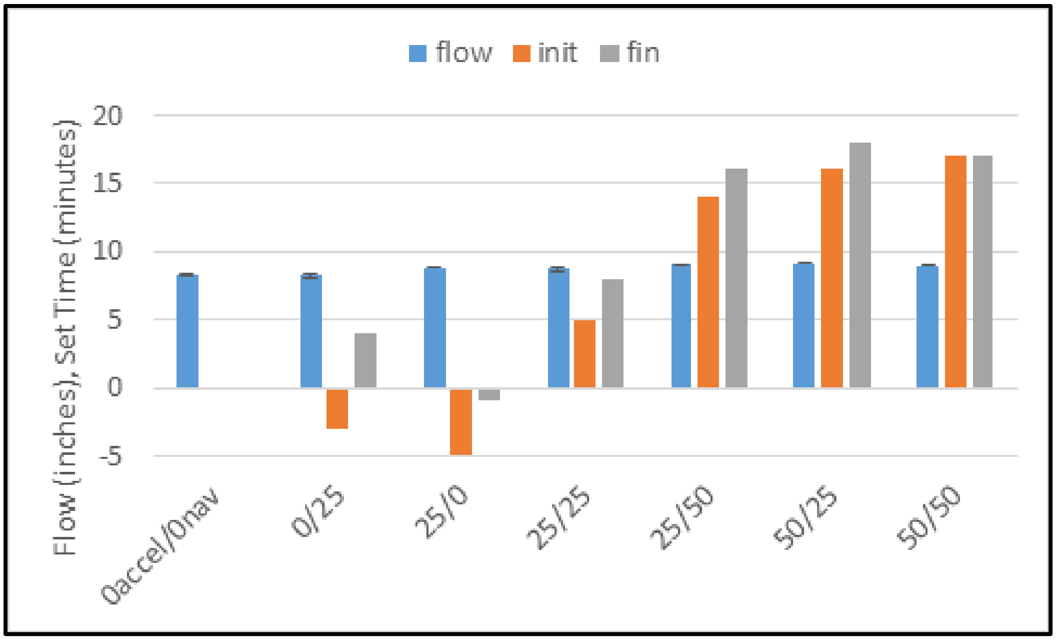
Figure 4-3. Flow and relative set time of various doses of Navitas.



4.5.3 Effect of combinations of accelerator and Navitas

When combining Navitas and accelerator at various doses, the flow responds similarly to using Navitas alone. The set time is significantly retarded by 14-18 minutes at higher doses (Figure 4-4). Based on this unexpected behavior, we recommend against combining Navitas and FP 20 accelerator.

Figure 4-4. Flow and relative set time of various combinations of accelerator and Navitas.



4.5.4 Effect of bentonite, shrinkage reducer, and superplasticizer

For these tests, bentonite was either added on top of the regular mixture design (1.5B, 3B, 250sup/6B) or added as cement replacement (3repl). SRA replaced water at a dose of 1.0 gal/yd^3. Superplasticizer (sup) was added on top of the regular mixture design, similar to common practice in the field.

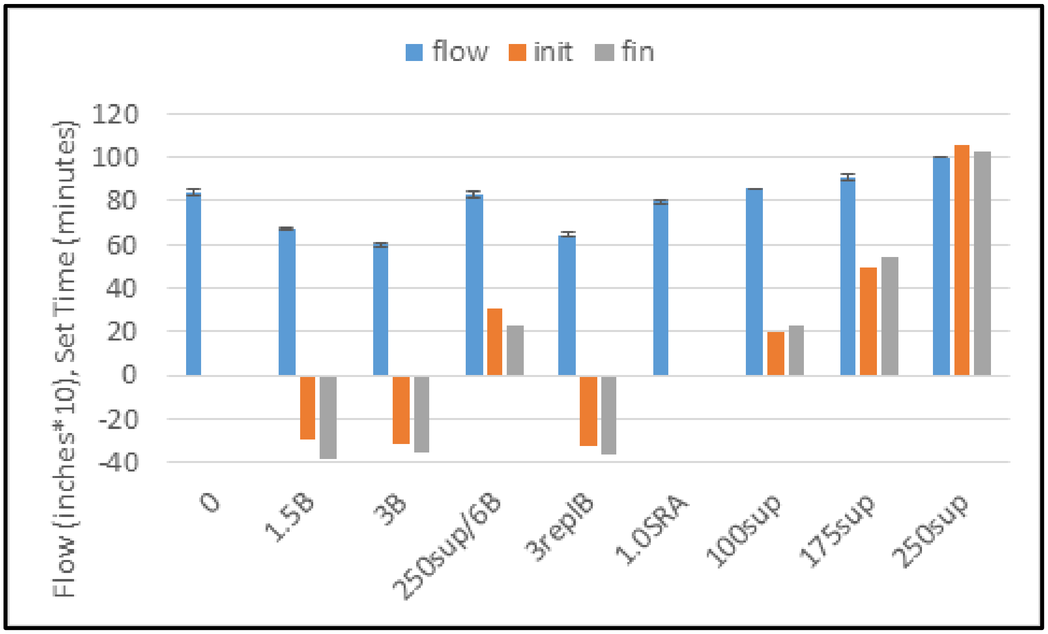
Shrinkage Reducer did not strongly affect flow. Superplasticizer provided the expected result of increased flow. Bentonite had a significant negative effect on flow. At 3%wt of cement, the bentonite mixture was stiff enough to overcome the thermal protection circuit of the Hobart mixer. Therefore, the maximum recommended dose of superplasticizer was added to the mixture with bentonite at 6%wt of cement. Flow of this mixture returned to the level of the control, but there was significant bleed water and some segregation of the paste on the flow table. Superplasticizer may be an effective tool to use in combination with bentonite, but only if both are used at moderate doses.

Shrinkage Reducer also did not significantly affect set time. This particular superplasticizer, while not marketed as a set retarder, had a very strong retarding effect on both initial and final set, ranging from about 20 to 50 to 100 minutes with increasing dose. Bentonite accelerated initial and final set by 30-40 minutes at both the 1.5% and 3% doses. The combination of

6% bentonite and the highest dose of superplasticizer retarded initial and final set by about 20-30 minutes.

Care should be exercised when using bentonite in a printing mixture to prevent setting in the pumping system (see Figure 4-5). Naphthalene sulfonate superplasticizer may aid both workability and setting challenges presented by bentonite.

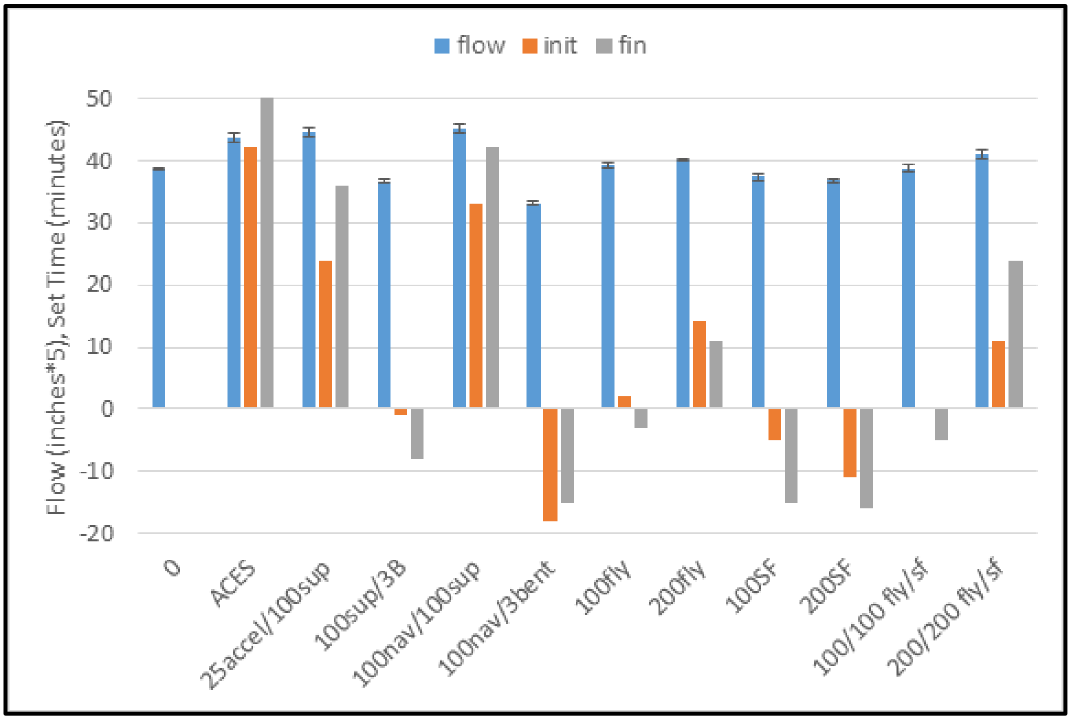
Figure 4-5. Flow and relative set time of bentonite, shrinkage reducer, and superplasticizer.



4.5.5 Effect of admixture combinations, fly ash, and silica fume.

The combination of admixtures in the ACES mixture (50accel, 100nav, 3B, 100sup, 100fly, 100SF) produced a flowable mortar with significantly retarded set (42 minutes initial, 50 minutes final) (Figure 4-6). A moderate dose of accelerator did not affect the retardation imparted by the superplasticizer. Combining moderate doses of superplasticizer and bentonite aided flow and resulted in nearly zero net effect on setting times. The combination of Navitas and superplasticizer significantly retarded set times. Navitas did not appear to affect the workability degradation and set acceleration imparted by bentonite. Fly ash tended to increase flow and slightly retard set, while silica fume tended to decrease flow and slightly accelerate set.

Figure 4-6. Flow and relative set time of admixture combinations, fly ash, and silica fume.



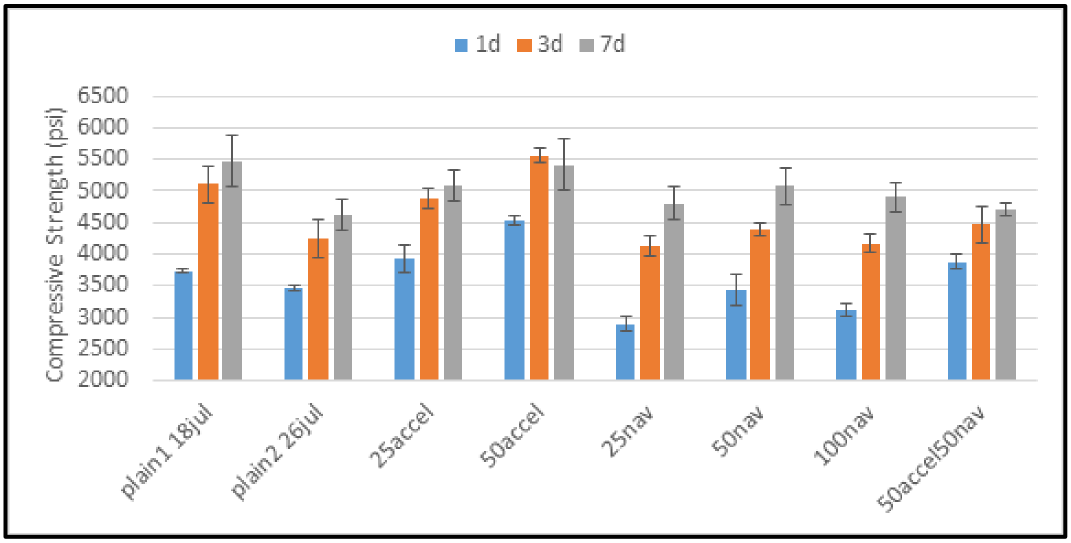
4.6 Compressive strength at 1, 3, and 7 days

Plain base mortar cubes were cast on the first and last days of testing to determine the variability of the experimental control baseline strength. Strength values are reported as the average of three specimens with standard deviation error bars.

4.6.1 Effect of accelerator and Navitas

Accelerator had the greatest effect at 1 day of age. At later ages, strengths were similar to the control mixtures. Navitas negatively impacted 1- and 3-day strengths. When combining accelerator and Navitas, 1-day strength improved, while 3- and 7-day strengths were similar to control mixtures (Figure 4-7).

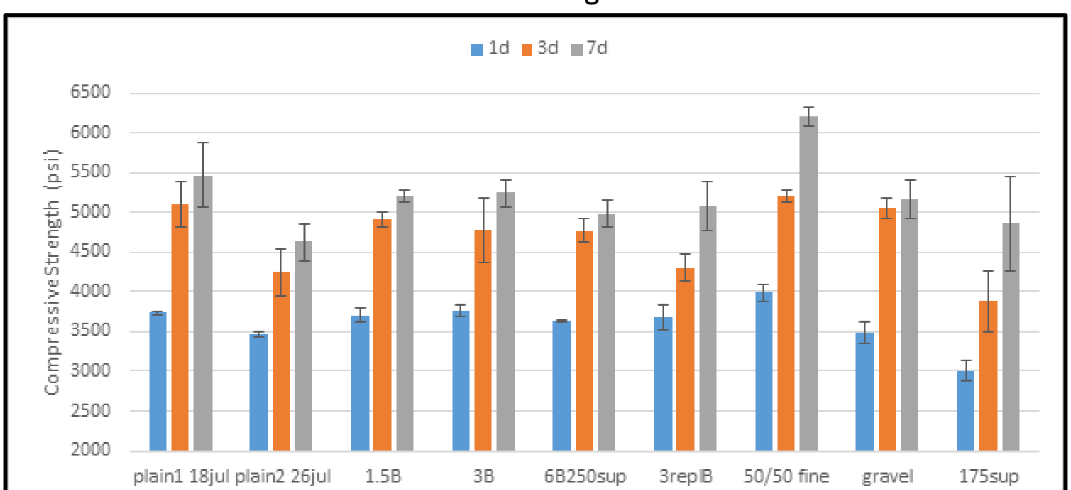
Figure 4-7. Compressive strength of mixtures containing accelerator and Navitas.



4.6.2 Effect of bentonite, superplasticizer, and aggregate gradation

Bentonite did not significantly affect strength at any age tested here, including at a high dose when combined with superplasticizer (Figure 4-8). Superplasticizer alone had a slightly negative effect on strength at all ages and increased the variability of strength. Substituting 50% of the #100 masonry sand with #8 fill sand improved strength at all ages, but this was likely caused by an error in moisture correction of the #8 fill sand, leading to a lower w/cm ratio. Including gravel in the mixture design with only #100 masonry sand had no significant effect on strengths at any age tested here.

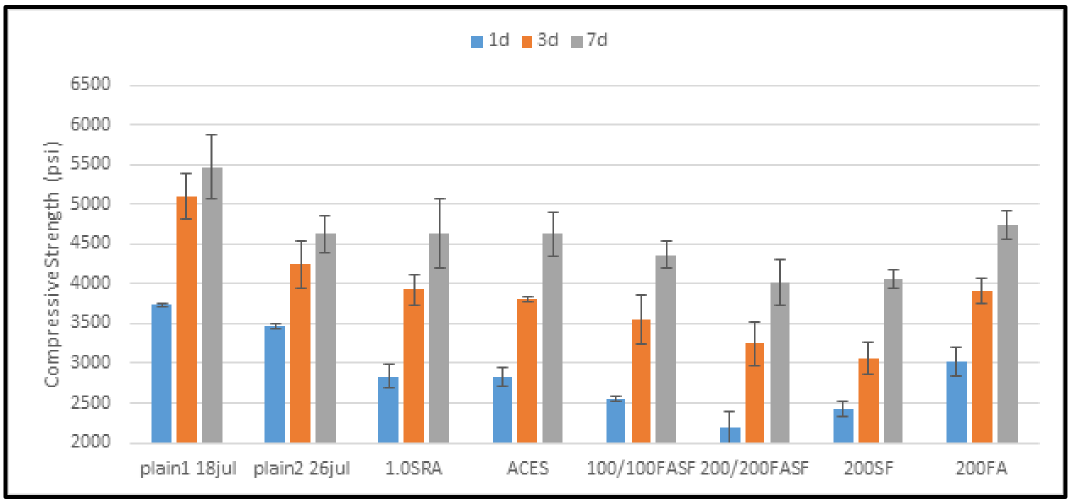
Figure 4-8. Compressive strength of mixtures containing bentonite, superplasticizer, and coarse sand or gravel.



4.6.3 Effect of fly ash, silica fume, shrinkage reducer, and a combination of admixtures

Shrinkage Reducer had a slight negative effect on strength at 1 and 3 days (Figure 4-9). Silica fume and fly ash negatively impacted compressive strengths at all ages tested here. It appears that the early age weakening effect of silica fume is stronger than that of fly ash. While these early age strengths are discouraging, it is expected that 28-day compressive strengths of mixtures containing fly ash or silica fume would meet or exceed the control. The combination of admixtures in the ACES mixture resulted in a slight negative effect on strength at 1 and 3 days.

Figure 4-9. Compressive strength of mixtures containing shrinkage reducer, a combination of admixtures, fly ash, and silica fume.



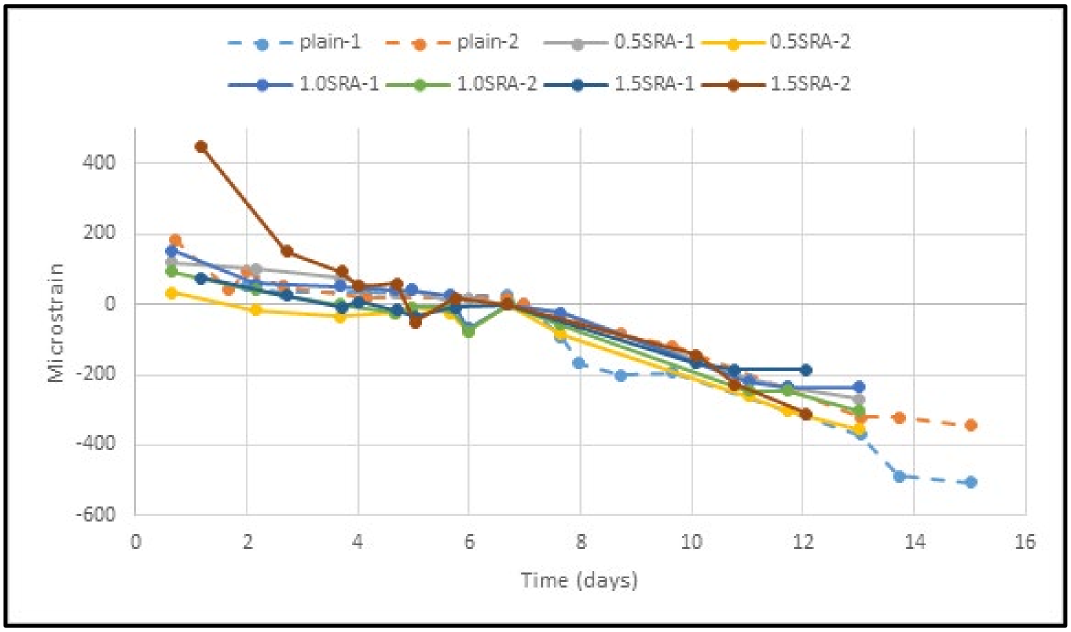
4.7 Drying shrinkage

Lowering the paste content while increasing aggregate fraction is the simplest method to reduce both drying and autogenous shrinkage in mortar and concrete. However, this would simultaneously increase viscosity and degrade the pumpability of the mix. In this test, each admixture was studied to determine its effects on drying shrinkage after 7 days of moist curing. While length measurements were taken during moist curing, the measurement immediately following removal from moist curing storage was chosen as the basis. At the time of this writing, there may not have been enough elapsed time to allow differences in shrinkage behavior to develop into measurable differences in length change. Repeated tests that apply lime-saturated water curing instead of moist curing may improve the resolution of drying shrinkage results.

4.7.1 Effect of shrinkage reducer

Shrinkage-reducing admixture did not have a significant effect on drying shrinkage in this test up to 14 days of age (Figure 4-10). Some shrinkage reduction may be observed during moist curing for certain specimens, but it lies within the noise.

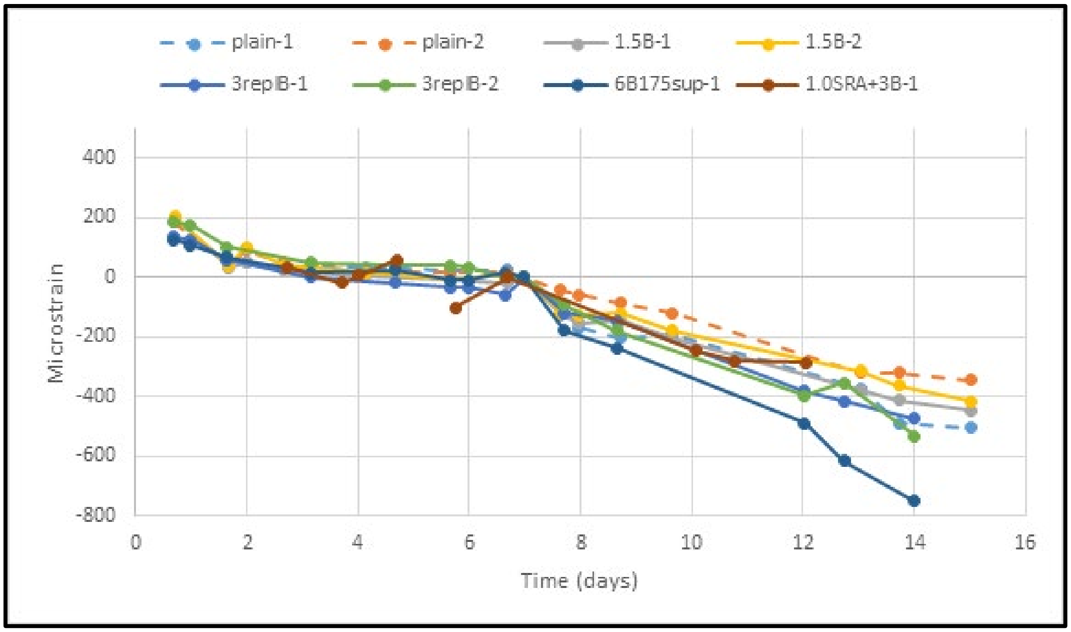
Figure 4-10. Length change of beams containing shrinkage-reducing admixture.



4.7.2 Effect of bentonite

Bentonite also did not exhibit significant shrinkage reduction (Figure 4-11). In fact, the specimen with the highest dose of bentonite and a moderate dose of superplasticizer actually enhanced shrinkage.

Figure 4-11. Length change of beams containing bentonite.



4.7.3 Effect of aggregate gradation

At the time of this writing, specimens containing 50% #8 fill sand and specimens containing gravel (1:2.25:1 cement:sand:gravel) were only 9 days old and did not have enough relevant data to report.

4.7.4 Use of fiber reinforcement

Shrinkage cracking was observed on walls of the prototype B-Hut printed in FY17 (Figures 4-12 and 4-13). While moist burlap and plastic covering successfully mitigated this drying shrinkage cracking, such methods may not be feasible to protect walls from shrinkage cracks in a production environment. Near the end of FY17, the Caterpillar prototype printer was used to test mixtures containing Strux 90/40 polypropylene structural macro fibers. Printed elements were completely devoid of shrinkage cracks at fiber doses of only 0.025 vol%, well below the manufacturer recommended dose. While flow alignment is almost certainly an issue associated with printing of fiber-reinforced concrete, the results clearly show adequate reduction of shrinkage cracking.

Figure 4-12. Drying shrinkage cracking approximately 1-2 hours after printing a wall section.

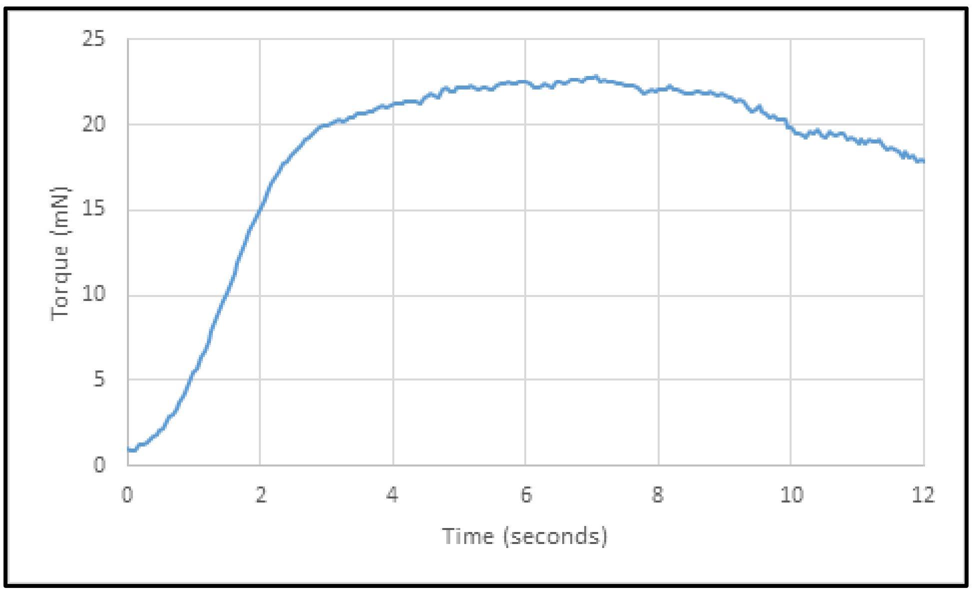
Figure 4-13. Fiber reinforcement completely mitigates shrinkage cracking in printed elements.

4.8 ICAR rheometer

In the previous sections, it was recommended to identify a suitable test to validate mixture rheological parameters to ensure suitability for additive construction. The ICAR rheometer was developed specifically for concrete mixtures, utilizing a 4-vane rotor and customized test chamber to deliver reproducible values of static and dynamic yield strength and plastic viscosity at a variety of shear rates.

In this test, we first measured the Stress Growth Curve (Figure 4-14) at a slow commanded rotation speed of 0.025 revolutions per second, which results in a maximum torque value that is reported as the static yield strength. The data acquisition rate is much faster than the acceleration of the vane to the commanded rotation rate, so we may observe the torque development over time as the vane begins to move. We then measured the Flow Curve, which averages the torque measured over a period of time at several different rotation rates. Tests were repeated three times, including removal of the rheometer and reconsolidation of the concrete by tapping the test chamber on the ground between tests.

Figure 4-14. Example Stress Growth Curve test using an ICAR rheometer at a commanded rotation speed of 0.025 revolutions per second.



Navitas exhibited nearly zero effect on the static yield strength immediately after mixing. This may not be true if the mixture is allowed time to set in the test chamber before testing, as we did observe some set acceleration when using Navitas.

We measured increasing static yield strength with increasing dose of bentonite, while superplasticizer had an extremely strong negative effect on static yield strength. When bentonite and superplasticizer are used together in the correct ratio, one may be able to achieve a target static yield strength. However, time-based increases in yield strength were observed when combining these admixtures. Further testing is required to determine the effects of time on this admixture combination.

Fly ash tended to reduce static yield strength while silica fume tended to increase it. The ACES mixture, though a complicated cocktail of everything tested here, exhibited only slightly lower static yield strength than both the control mixtures.

Figures and further discussion on this topic are reserved for a peer-reviewed publication to be submitted after filing of this report.

4.9 Conclusions

1. Since Navitas significantly increases cost while reducing strength without any apparent impact on rheology, this report recommends suspending the use of Navitas in printing mixtures.
2. As shown in the data to be published elsewhere, it is possible to design a simple mixture of water, cement, and aggregates to achieve a printable mix with static and dynamic rheological properties similar to an empirically good printing mix. In the absence of proper aggregate gradations and control over the ratios of water/cement, sand/cement, and gravel/cement, the admixtures studied here can help the mix designer produce a printable mix by following the rules of thumb in Table 4-3.
3. Further testing is required to better understand the time-dependent rheological effects of superplasticizer alone and superplasticizer mixed with bentonite or silica fume to avoid slump loss and setting in the pump. These time-dependent properties may be useful in developing a mixture for high-speed printing. Such a mixture would be capable of holding greater self-weight at earlier times, even when accelerator is not available.
4. Future ACES work might include calculating the strength required to support N layers of printed material. Then, based on the speed of layering, determine whether accelerator is needed or if the structure can simply rely on the static yield strength and advanced initial set time imparted by silica fume or bentonite.

Table 4-3. Rules of thumb for admixtures tested in this report.

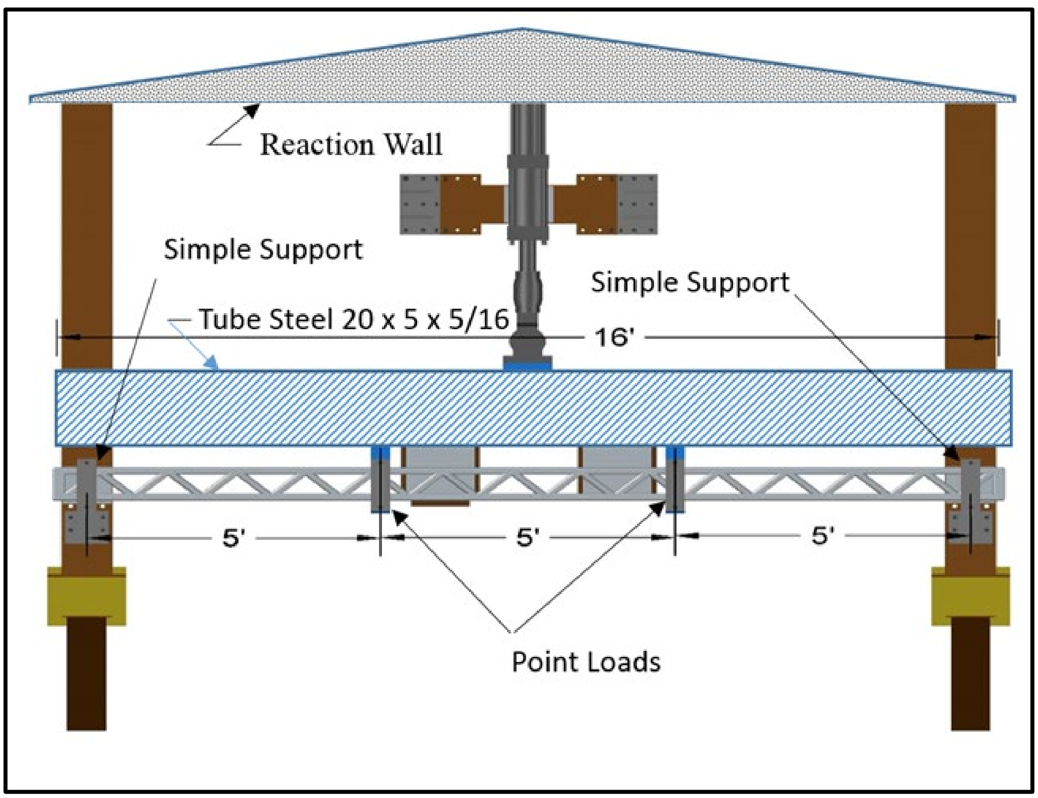
Admixture	Set Time	Early Strength	Rheological Parameters
Accelerator	↓↓	↑↑	Not Tested
Navitas	↓	↓	O
Superplasticizer	↑↑	↓	↓↓
Shrinkage Reducer	O	↓	Not Tested
Bentonite	↓↓	O	↑↑
C Fly Ash	↑	↓	↓
Silica Fume	↓	↓↓	↑↑

5 Stress Testing

5.1 Full-scale flexural testing

Existing reinforced concrete code for monolithic or precast construction may not address issues specific to layer-printed structural elements. In an effort to guide the design of roof structures for B-Huts, beams printed using ACES 2 were tested in third-point bending at full scale. Dimensions in plan were approximately 16-ft. by 8-in. and the printed layers resulted in a height of about 5.5-in. The beams were tested over a 15-ft. clear span in a custom load frame with string potentiometers attached at the center and two middle loading points of the beam. Beams were constructed with various reinforcement schemes consisting of one or more of steel rebar, basalt rebar, aramid mesh, or basalt mesh. Figure 5-1 shows an aerial schematic of the custom load frame.

Figure 5-1. Aerial schematic of custom load frame.



Beams were tested in the positive and negative direction to actuator displacements of 1.5, 3.0, and 4.5 in. Each loading and unloading segment of the test was performed over 12 minutes, so displacement rates were 0.5, 1.0, and 1.5 in. per minute, respectively. Table 5-1 lists and Figures 5-2 and

5-3 show example data from Beam 4, which was doubly reinforced by #3 deformed steel rebar. This example and most other beams generally achieved maximum load in the second loading cycle, which was the first loading cycle in the negative direction. Most of the beams failed in diagonal tension outside the center section at nodes where horizontal chords met infill webs. Basalt and aramid meshes tended to improve strength and ductility before failure, but did not affect post-peak behavior.

Table 5-1. Minimum and maximum values of raw data.

	String Pot 1		String Pot 2		String Pot 3		Load Cell		Actuator	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Peak 1	1.35	-1.08	1.51	-1.51	1.25	-1.86	2662.42	-3181.87	1.50	-1.50
Peak 2	2.05	-2.07	2.91	-2.93	3.40	-3.78	892.35	-2571.50	3.00	-3.00
Peak 3	4.53	-2.48	6.14	-2.67	6.85	-3.60	981.83	-3360.95	4.49	-4.51

Figure 5-2. Displacement vs time for the three string potentiometers and the actuator (Beam 4, rebar on both sides).

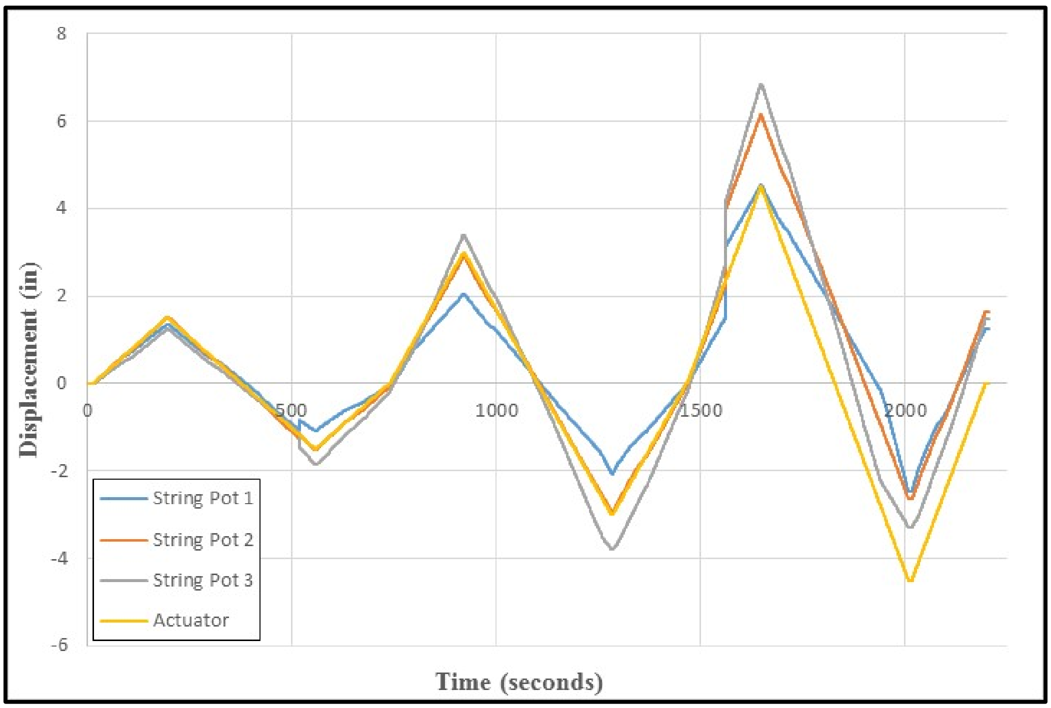
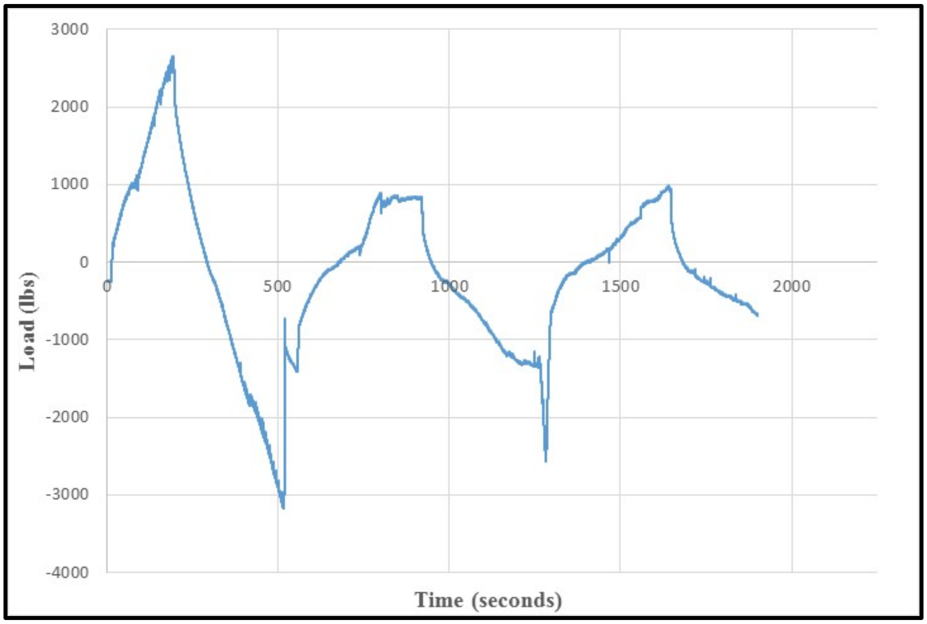


Figure 5-3. Load vs. time (Beam 4, rebar on both sides).



The test results and observations made by researchers uncovered a critical deficiency with traditional concrete beam reinforcement schemes. Shear reinforcement at the nodes would be required to improve the capacity of the beams. In addition, the relatively large size of reinforcement and relatively small area of concrete engaging the reinforcement resulted in a long developmental length, thus inhibiting proper load transfer to the reinforcement and encouraging spallation of concrete. Further discussion of the results and additional figures, including photographs and hysteresis plots, are reserved for a peer-reviewed publication submitted to the American Concrete Institute (ACI) Structural Journal in FY17.

5.2 Diagonal compression testing

Seismic design may be required for structures produced by ACES hardware, but once again, existing building code may not adequately account for deficiencies specific to layer-printed elements. Wall sections were printed for testing and analysis according to ASTM E519, which places a wall section in compression along the diagonal axis to impart an effective shear load on the wall.

In total, 10 tests were performed on wall sections in various loading scenarios, including in-plane and out-of-plane compression. The bulk of figures and discussion of results has been reserved for a peer-reviewed publication that is in preparation at the time of this writing. Figure 5-4 shows an example load-displacement curve from a diagonal compression test (Figure 5-5). Linear Variable Displacement Transducers (LVDTs) were affixed to the specimen vertically and horizontally to capture actual shear displacements.

Figure 5-4. Load-displacement and LVDT extension during a diagonal compression test.

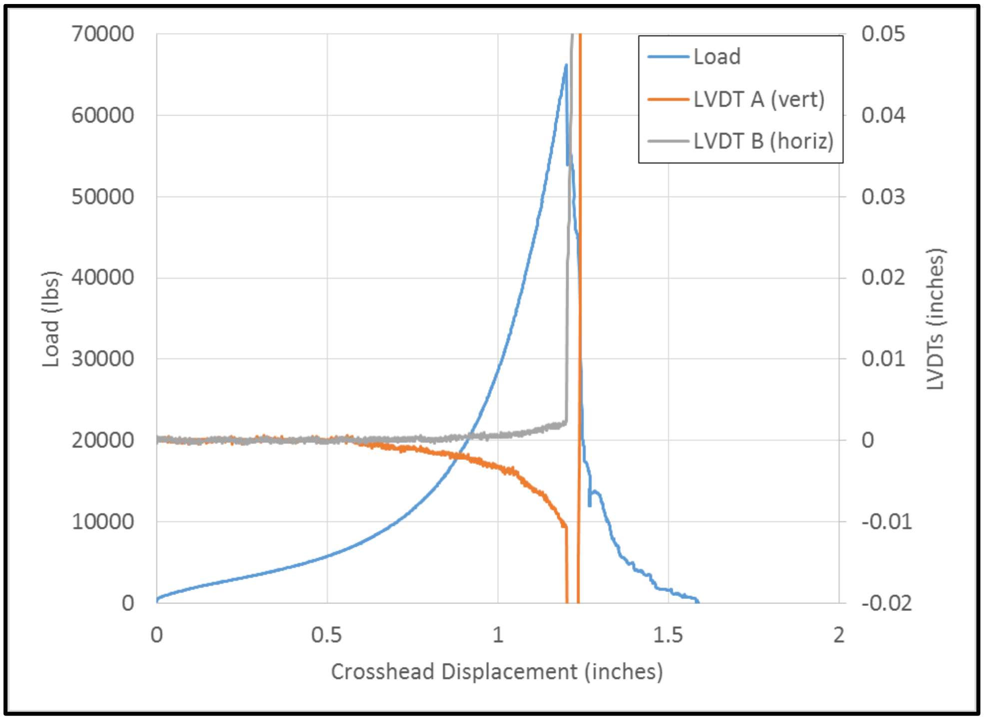


Figure 5-5. Example photos of test specimens before (left) and after (right) testing.

Analysis of loads and displacements experienced by the wall sections indicate similar behavior as comparable CMU wall sections. However, the failure modes were unique. Most printed specimens failed first by a vertical crack through the center of the specimen, followed closely by sliding or cracking along a cold joint between layers that were printed days, or even hours, apart. The presence of basalt or aramid mesh between layers seemed to encourage the sliding behavior. Finally, the corners of the specimens near the loading shoes would crush before the specimen completely failed and fell out of the fixture.

Overall, the layer-printed elements performed much better in these diagonal compression tests than in the beam tests. The sliding failure mode could have significant implications for life safety inside a B-Hut during seismic events. Reinforcement or fill for shear walls should be carefully considered in future work.

5.3 Blast load simulator testing

A variety of wall section designs were printed using ACES 1 at ERDC-CERL and delivered to ERDC-GSL for testing on the BLS, as outlined in the original Project Management Plan. These tests are expected to expose any irregular dynamic responses or design deficiencies of additively manufactured walls that are subjected to blast loads. At the time of this writing, tests were scheduled, but had not been performed.

Specimens include two printed wall sections with dimensions of approximately 32x32x8-in., one cast-in-place wall section with similar dimensions and an infill pattern designed to mimic the printed wall sections, one wall section assembled from reinforced beam sections, and two concrete masonry unit (CMU) wall sections (Figures 5-6 to 5-9). All specimens will be simply supported in one-way loading, since two-way support may prevent failure during testing. One of each of the printed and CMU specimens will experience an applied vertical load during testing to simulate roof and snow loads that a typical B-Hut wall would experience.

Figure 5-6. Planned wall section test configurations (subject to modification).

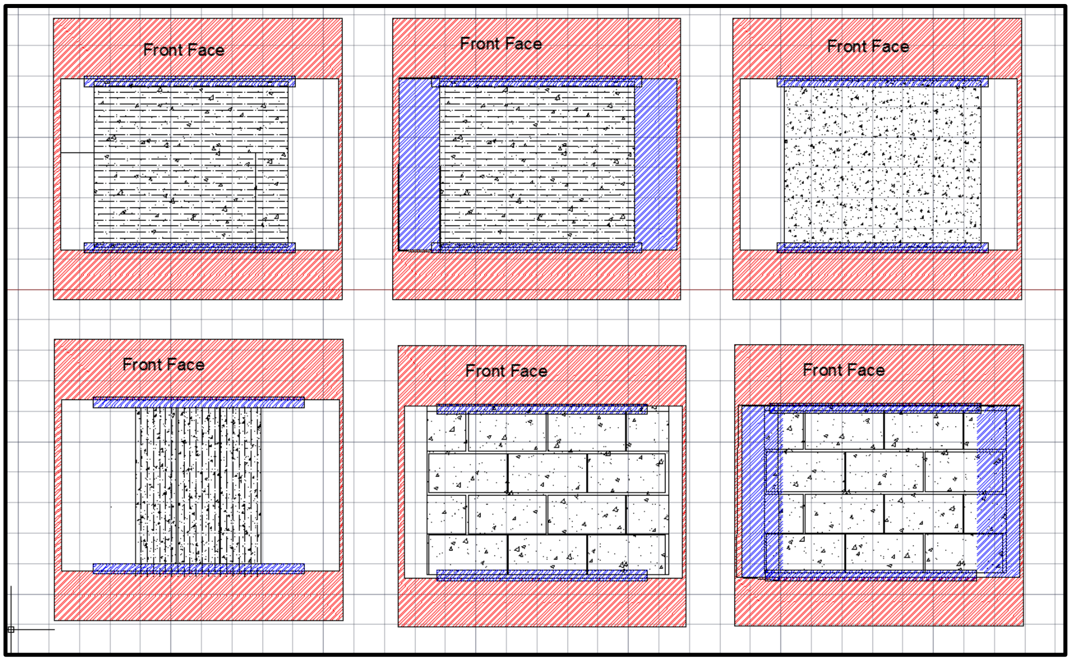
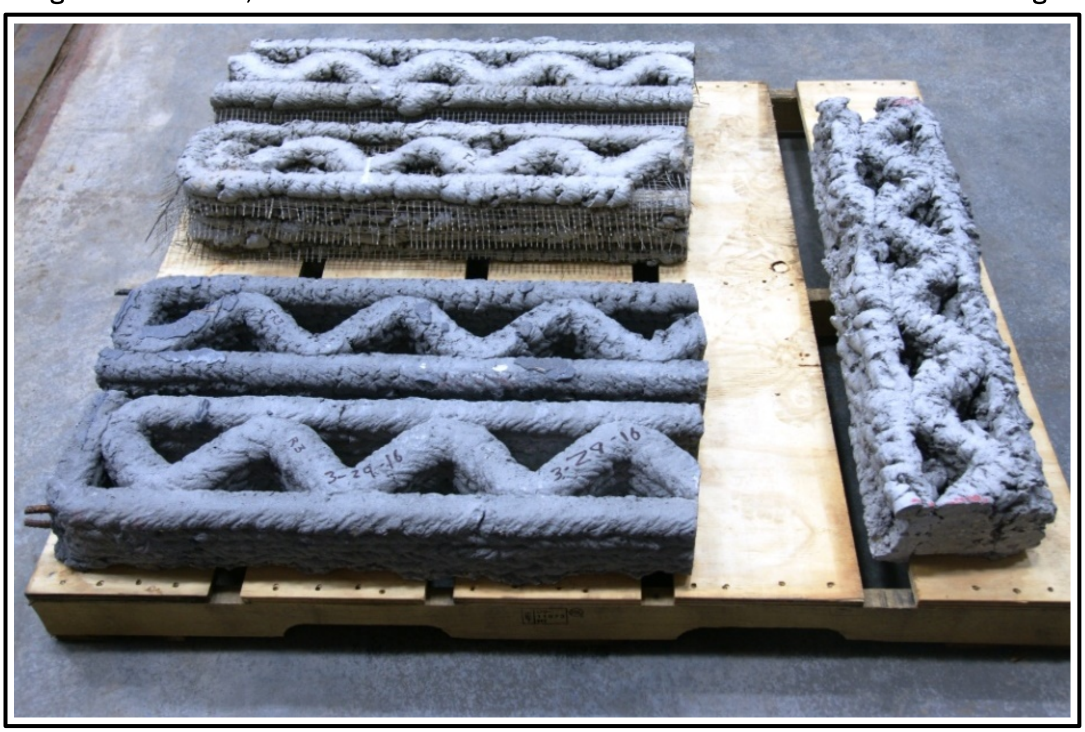


Figure 5-7. Printed wall section for BLS testing.

Figure 5-8. Cast-in-place wall section for BLS testing.

Figure 5-9. Printed, reinforced beam sections to be assembled with mortar for BLS testing.



6 Conclusions and Recommendations

6.1 Concrete mixtures for additive construction

6.1.1 Conclusions

This stage of work concluded that a conventional mixture design containing a typical proportion of coarse aggregate will not be adequate for additive construction applications because of insufficient flow through a nozzle apparatus. To allow for adequate flow, the concrete material must include a large proportion of fine materials such as sand, but it can still incorporate a significant content of coarse (⅜-in.) aggregate, which is expected to reduce shrinkage. Chemical admixtures and additives appeared to have varying degrees of success in aiding flow and shape stability. The addition of fly ash provided the best improvement in flow, while the addition of bentonite provided the best shape stability. The use of superplasticizer significantly increased fluidity of the mixture, but its use should be accounted for by reducing the water content of the mixture in the future.

Little correlation was observed between the results of the empirical drop table test and the qualitative extruder test. Although both the extruder and the drop table were used to determine flow characteristics of each material under some externally applied stress condition, there were two notable differences in these tests: (1) the extruder test provided a degree of confinement due to the presence of the funnel, as opposed to the unconfined condition experienced in the drop table test, and (2) the extruder test relied on a steadily applied pressure to induce flow, whereas the drop table produced a repeated acute stress, like an impulse load.

6.1.2 Recommendations

Broadly, this study demonstrated the ability to include coarse aggregates in a mixture for 3D concrete printing. Though the effects of the additives were evaluated one by one, an optimized mixture will likely include a combination of the testing additives, e.g., the base 1:3:1 concrete mixture, plus silica fume, plus SP, plus fibers. It is recommended that such material combinations, as well as pumping through a real nozzle configuration, be the next subjects of study.

It was expected that the dynamic impact associated with the drop table played a key role in the difference between the two tests. A possible inference from this observation is that materials that flow poorly in the extruder but flow better on the drop table (e.g., B0, B2, and B5) could benefit from applied vibration during extrusion. The use of the drop table and the manual extruder apparatus together was intended to provide an easily attainable indication of how a test material would flow in an additive construction process that involves large-scale material extrusion of concrete through a nozzle. It is recommended that follow-on experiments be performed in an actual additive construction, or large-scale additive manufacturing setup using a custom 3D concrete printer. Then, observations from the applied test can be compared with the drop table and extruder results to better determine the utility of the two flow tests.

Experiments showed that the addition of short reinforcing fibers did not reduce flow, and in fact appeared to aid flow in most cases. The inclusion of fibers improved shape stability of the fresh materials to some extent. Considering that the nylon fibers are hygroscopic and tend to absorb water from the mixture, it is recommended that the use hydrophobic fibers such as polypropylene be considered as the subject of future research.

6.2 Development of mixture formulas and materials

6.2.1 Conclusions

This initial laboratory testing successfully prepared the basis for test methods useful for additional performance testing to optimize the concrete mixture and to use as quality control/quality acceptance methods for other candidate mixtures. Regarding the types of additives used in the test mixtures, this work concluded that:

1. Type III cement did not show an overall benefit when compared to Type I/II cement in the Baseline mixture, in particular as related to set time. Type III cement should not be considered for further study.
2. Metal fibers improved the tensile strength of the material compared to the Baseline mixture.
3. The chemical admixtures in the plastic state, such as slump, performed similarly to the Baseline mix. Of the chemical admixtures, the Accelerator clearly showed benefit for a significantly set time, and early compressive and tensile strengths.

4. The addition of supplemental cementitious materials such as fly ash and silica fume resulted in slower setting times, impacted slump (fly ash increased slump, silica fume decreased slump), and gave mixed results related to strength.
5. The addition of bentonite in the mixture appeared to provide some shape stability. In the plastic state, Mix 7 was stiffer with a lower slump and flow compared to the Baseline mix. The initial set time was comparable to the Baseline and longer for final set. Generally, the strength properties of Mix 7 were lower than those of the Baseline. The 28-day compressive strength decreased.

6.2.2 Recommendations

Regarding the types of additives used in the test mixtures, this work recommends that:

1. A test mixture that included nylon fibers (designated as Mix 4) was not tested. It is recommended that nylon fibers be evaluated and tested as an additive for concrete mixtures for additive construction.
2. The extrusion test is qualitative only. Innovation is needed to quantitatively determine a concrete mixture's characteristics.
3. While the slump and flow table tests are commonly used, it was difficult to relate the measurements from either test to the plastic state of the mixture. These tests should be re-evaluated for their suitability for additive construction.
4. At the completion of mixing, the concrete mixture is continually changing due to the interaction of cement, water, and additives, and also due to the time elapsed when the material enters the delivery system until it is extruded out of the nozzle. These test methods will be useful to further determine the material characteristics as the quantity of material is scaled up and uninterrupted material mixing/printing is introduced. Since additive construction is in the early developmental stages, it is recommended that additional modifications and new methods for mixture characterization be developed.
5. Metal fibers improved the tensile strength of the material compared to the Baseline mixture. Overcoming the tendency for fibers to clog within the delivery system will offer a significant benefit for the inclusion of fibers in the mixture. This will need to be weighed against the material benefit. The test data were limited, however, and additional testing is recommended. `

6.3 Rheology and setting quantification

6.3.1 Conclusions

This work concludes that it is possible to design a simple mixture of water, cement, and aggregates to achieve a printable mix with static and dynamic rheological properties similar to an empirically good printing mix. In the absence of proper aggregate gradations and control over the ratios of water/cement, sand/cement, and gravel/cement, the admixtures studied here can help the mix designer produce a printable mix.

6.3.2 Recommendations

Since Navitas significantly increases cost while reducing strength without any apparent impact on rheology, this report recommends suspending the use of Navitas in printing mixtures. Further testing is required to better identify and quantify the time-dependent rheological effects of superplasticizer alone and superplasticizer mixed with bentonite or silica fume to avoid slump loss and setting in the pump. These time-dependent properties may be useful in developing a mixture for high-speed printing. Such a mixture would be capable of holding greater self-weight at earlier times, even when accelerator is not available.

It is recommended that future ACES include calculations of the strength required to support N layers of printed material, and then, based on the speed of layering, to determine whether accelerator is needed or if the structure can simply rely on the static yield strength and advanced initial set time imparted by silica fume or bentonite.

6.4 Stress testing

6.4.1 Conclusions

The test results and observations made in this work indicate a critical deficiency with traditional concrete beam reinforcement schemes. The relatively large size of reinforcement and relatively small area of concrete engaging the reinforcement resulted in a long developmental length that inhibited proper load transfer to the reinforcement and encouraging spallation of concrete. This work concludes that shear reinforcement at the nodes be used to improve the capacity of the beams.

Analysis of loads and displacements experienced by the wall sections indicate a behavior similar to that common to comparable CMU wall sections although the failure modes were unique. Most printed specimens failed first by a vertical crack through the center of the specimen, followed closely by sliding or cracking along a cold joint between layers that were printed days, or even hours, apart. This work found that the presence of basalt or aramid mesh between layers seemed to encourage the sliding behavior. Finally, the corners of the specimens near the loading shoes would crush before the specimen completely failed and fell out of the fixture.

6.4.2 Recommendations

This work found that, overall, the layer-printed elements performed much better in these diagonal compression tests than in the beam tests. The sliding failure mode could have significant implications for life safety inside a B-Hut during seismic events. It is recommended that reinforcement or fill for shear walls be considered in future work.

It is also recommended that seismic design be required for structures produced by ACES hardware.

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Acronyms and Abbreviations

Term	Definition
ACES	Automated Construction of Expeditionary Structures
ACI	American Concrete Institute
AFCS	Army Facilities Component System
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BLS	Blast Load Simulator
CBA	Capabilities Based Assessment
CERL	Construction Engineering Research Laboratory
CMU	Concrete Masonry Unit
CBRN	Chemical, Biological, Radiological, and Nuclear
CRADA	Cooperative Research and Development Agreement
CRREL	Cold Regions Research and Engineering Laboratory
C-S-H	Calcium Silicate Hydrate
DOE	U.S. Department of Energy
DOT	Department of Transportation
ERDC	U.S. Army Engineer Research and Development Center
ERDC-CERL	Engineer Research and Development Center, Construction Engineering Research Laboratory
ERDC-CRREL	Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory
ERDC-GSL	Engineer Research and Development Center, Geotechnical and Structures Laboratory
ERS	Engineering Resilient Systems
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FRWR	Full-Range Water Reducer
GSL	Geotechnical and Structures Laboratory
HDPE	High Density Polyethylene
HRWR	High Range Water Reducer
ID	Identification
IESNA	Illuminating Engineering Society of North America
ISARC	International Symposium on Automation and Robotics in Construction
JIIM	Joint, Interagency, Intergovernmental, and Multinational
KSC	Kennedy Space Center
LVDT	Linear Variable Displacement Transducer
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration

Term	**Definition**
NSN	National Supply Number
OMB	Office of Management and Budget
PP	Polypropylene
PRC	People’s Republic of China
RCA	Rheology-Controlling Admixture
RMA	Rheology-Modifying Admixture
SAR	Same as Report
SCM	Supplementary Cementitious Material
SF	Standard Form
SP	Superplasticizer
SRA	Shrinkage-Reducing Admixture
TR	Technical Report
TRADOC	U.S. Army Training and Doctrine Command
UHPC	Ultra-High Strength Concrete
USC	University of Southern California
USDOT	U.S. Department of Transportation
w/c	Water-to-Cement Ratio

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14. ABSTRACT
Complex military operations often result in U.S. forces remaining at deployed locations for long periods. In such cases, more sustainable facilities are required to better accommodate and protect forward-deployed forces. Current efforts to develop safer, more sustainable operating facilities for contingency bases involve construction activities that require a redesign of the types and characteristics of the structures constructed, that reduce the resources required to build, and that decrease the resources needed to operate and maintain the completed facilities. The Automated Construction of Expeditionary Structures (ACES) project was undertaken to develop the capability to “print” custom-designed expeditionary structures on demand, in the field, using locally available materials with the minimum number of personnel. This work investigated large-scale automated “additive construction” (i.e., 3D printing with concrete) for construction applications. This report, which documents ACES materials and testing, is one of four technical reports, each of which details a major area of the ACES research project, its research processes, and its associated results. There major areas include System Requirements, Construction, and Performance; Energy and Modeling; Materials and Testing; Architectural and Structural Analysis.

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