CIVE 4043

Concrete 3-D Printing Team

Final Report

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I. Team Information

The Spring 2020 Concrete 3D Printing Group is composed of ten student members and three faculty advisors. The students and advisors encompass civil engineering, mechanical engineering, and electrical engineering. The civil engineering group consists of Jake Flaspohler, Christopher Filip, Trevor Galusha, Rachel Schwarz and faculty advisor, Dr. Tyler Ley. The mechanical engineering group consists of Jesse Bowser, Jonah Bryant, Taylor Bunch, Bailey James and faculty advisor, Professor Jim Beckstrom. Lastly, the electrical engineering group consists of Erick Gonzalez, Drew Stark and faculty advisor, Dr. Nishantha Ekneligoda. Drew Stark is the electrical team lead, and Bailey James is the mechanical team lead as well as the overall team leader. This document will focus on all three groups' work towards the end-goal of the project. While the groups will work interdependently, the work specific to each group will be divided up by engineering type.

CIVE Team Members

Chris Filip (CIVE Team Lead)
Has around two years of experience working as a research assistant for Dr. Ley at Bert Cooper Engineering Laboratory. Experience includes mixing and testing of fresh and hardened concrete specimens. Has taken multiple classes involving Construction Materials, Concrete Materials and Mixture Design, Reinforced Concrete Design, Steel Design, and Prestressed Concrete Design. Will bring experience, knowledge, and commitment to this project.

Jake Flaspohler
Worked as an undergrad research assistant for Dr. Ley for a semester at Bert Cooper Lab. Work includes mixing concrete and running fresh and hard concrete tests. Has taken design courses at Oklahoma State including Reinforced Concrete Design, Concrete Mix Design, and Steel Design. Able to use Microsoft Office, AutoCAD, and MicroStation. Will bring teamwork and commitment to the project.

Trevor Galusha

Has worked for Dr. Hartell as an Undergraduate Research Assistant for over a year focusing on concrete monitoring and testing methods. Had the opportunity to focus on the structural integrity of the I-235 Bridge which allowed for AutoCAD experience and some MATLAB basics. Has taken numerous design courses at Oklahoma State University such as Reinforced Concrete Design, Steel Design, Concrete Mixture Design, and Timber Design all of which will aid in this design project. Has applicable knowledge of Microsoft Office suite, VBA, AutoCAD, MATLAB, Risa 2D, and Mastan 2D. Will bring experience, commitment, and organization to this project.

Rachel Schwarz

Has one year of experience working as a research assistant at Oklahoma State University under Dr. Tyler Ley involving research in hardened air voids analysis (HAV). Is head person in charge of HAV, managing the preparation of samples. Has taken multiple courses at Oklahoma State related to structures and materials, including Reinforced Concrete Design, Steel Design, Concrete Mix Design, and Timber Design. Knowledgeable in Microsoft Office, VBA, AutoCAD, and Risa. Will bring structure and commitment to this project.

II. Introduction

The overall scope of this project is to develop a system that is capable of 3-dimensionally printing a regular concrete mixture. It is hopeful that this concrete mixture will be able to provide extremely affordable homes to the people in need. Three dimensional printing has been accomplished all over the world with the use of mortar. However, this poses numerous problems to the ethical, sustainable engineering aspects. Mortar is a concrete mixture without the use of coarse aggregates. While this sounds like a good idea because printing is easier with it, it is much more expensive. Coarse aggregates make up anywhere from 40 to 65% of a concrete mixture. This is a large amount of space in the concrete that is occupied by inexpensive aggregates rather than cement. Cement is the most expensive component of a concrete mixture. With this known, it makes sense economically to limit it as much as possible. Also, cement has a high CO2 footprint. It is the goal of this team to limit this as affordable housing should not come at a higher cost to the environment. Overall, this team will aim all efforts towards furthering the progression of sustainable and affordable homes.

III. COVID-19 Addendums

Team Project Proposal Changes

Due to COVID-19, the problem description for this semester was tackled a little differently than stated in the project proposal. The problem for 3-D printing still exists, but the end-goal changed to virtual models and detailed deliverables to expedite the future semester's work on this project. ZARP believed in the work accomplished and provided evidence alongside factual observations to prove or suggest the need for a vibration technique, dual extrusion, and pulp curing; all of which could enhance the concrete aspect of the project.

The mechanical engineers on the project were not able to complete a working system. With this known, the project scope changed to virtual work. Therefore, the proposal has changed more so to virtual work and extremely detailed and informative deliverables. The mechanical and electrical engineers will create a virtual model for the overall system.

While there will not be a wall produced from the mechanical system at the end of the semester, the civil engineers still created two walls this semester without the use of formwork. One being single extrusion and the other being dual extrusion. These will be elaborated on throughout this report.

The civil engineers worked with the data they acquired from coring and mixing this semester in order to provide insight on vibration techniques, dual extrusion, and pulp curing. The original proposal of further bettering the mixture design was not enacted as the laboratory became off limits before this testing was initiated. ZARP believes dual extrusion is the method for the future hence this report will attempt to shed light on why it is a great option and how it could be further investigated. From coring, there is evidence that supported the need for a slight increase in strength if possible. This is the primary reason behind exploring a pulp cure method. Lastly, much work was completed this semester towards finding a vibration technique as will be shown throughout this report. Therefore, ZARP's, or the civil engineers, proposal will be providing significant information on dual extrusion, pulp cure, vibration techniques, and future testing that needs to be completed to fully prove the need for these components.

Project Constraints Alterations

The constraints within section VI were still valid for the overall 3-D printing project, however, the pandemic that swept the nation and that shut down parts of campus presented additional constraints. Some of the noted constraints were not necessarily pertinent to this project's semester end goals due to no physical deliverables being allowed this semester.

For the electrical and mechanical engineers, the primary constraints shifted to not having access to the physical components as well as not being able to work together to gain hands-on operating experience. The electrical engineers were still able to go through the necessary coding process;

however, they were not able to perform any trials with the skid steer which was vital. The mechanical engineers were still able to create the virtual models; however, the mechanical system has never worked, and trials were a necessity. Therefore, the future group will have the necessary information, but will need to perform trials in order to ensure the system operates properly.

The civil engineers work revolved around trial and error as this work has never been done before with concrete. With not having access to the lab, the work ceased. The civil engineers focus shifted to completely document the work accomplished as well as provide insight for future groups to further investigate the civil components of the project.

IV. Project Problem Statement and Project Proposal

A. Problem Description

ZARP was given the objective of creating a 3-dimensional concrete printer with the primary goal of making a skid steer autonomously print a sinusoidal shaped wall. Last year, the use of an overhead crane was attempted and was not able to properly produce the wall due to mechanical failures. However, this year, in hopes of allowing the printer to be used on job sites and all over the world, the goal was to be able to mount the system to a skid steer and have it be remotely controlled to produce the wall. In the future, the goal is to be able to create an entire home on site with this method.

The goal of this semester was to create a wall that was approximately five foot in length, three foot in height, eight inches thick, and have a magnitude of six inches for the sinusoidal wave. However, the subgroups believed that this was a far stretch goal due to the mechanical errors from the previous semester. With this known, ZARP planned on attempting a straight wall with no formwork that is five foot in length, three foot in height, and eight inches in thickness. The purpose of this concrete mixture was to utilize the coarse aggregate found at Bert Cooper Engineering Laboratory as well as include tensile reinforcement, i.e. rebar. Upon conducting a sieve analysis, it was found that the coarse aggregate to be used had a maximum nominal aggregate size of 1 inch.

B. Team Project Proposal

Our proposal consisted of continuing the improvement of the mixture design that worked in Fall 2019. Due to time restrictions, the full optimization of the concrete mixture design was not achieved. However, the civil engineers worked towards bettering the concrete aspect of the project. The primary goal was to ensure sustainability, pumpability, and to allow it to hold a sharp, beautiful finished edge. ZARP attempted numerous methods and mixture designs to combat problems encountered. The team proposed a consolidation method that works alongside the mechanical printer to properly consolidate the wall. This allowed for cohesion to the tensile reinforcement, provided a more workable exterior, and produced an in-place structure closer to the design values. ZARP ran numerous quality control tests to investigate where the mixture could be improved.

For this semester, because of the potential problems of increasing the difficulty of the wall shape with regards to the other disciplines, the engineers on the project decided to produce a straight wall with no formwork. This included finding a proper way of consolidating the wall, and producing a way to cure the wall in hopes of providing an in-place concrete structure closer to the design strength values. The mechanical engineers were focused on fixing the problems from last semester and figuring a way to mount the hopper to the skid steer. This included producing a working solution in connecting their system to the hydraulic power of the skid steer as well as fixing this issue of concrete not being able to extrude from the system. The electrical engineers oversaw communicating with the skid steer via electronics and controlling the print autonomously.

Overall, the team proposal was to get past the hurdle from last semester of not being able to see the mixture come out of the auger system. Once the mechanical engineers could provide a working system, the electricals could simultaneously be working on the autonomous aspects. After the system is complete, the civils could see the system in action and further improve the design of the concrete where needed. However, until this time is reached, the civils primarily focused on consolidation methods and increasing in-place compressive strength as this is deemed the solution to numerous problems in the concrete industry.

C. Client Contact Information

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V. Applicable Codes and Standards

A. Civil Engineering

It should be noted that the previous semesters' civil engineers came up with a workable mixture using the standards below. ZARP focused on figuring out the in-place properties and procuring an effective consolidation technique. For determining the hardened properties, ASTM C39, ASTM C42, and ASTM C642 were utilized. This semesters' engineers followed the standards in creating new concrete to test differing consolidation methods as well as altering the mixture if or when necessary.

ASTM C39 - Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

- This test method covers determination of compressive strength of cylindrical concrete specimens such as molded cylinders and drilled cores.

ASTM C42 - Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete

- This testing method covers the acceptable methods that are allowed when it comes to taking cores of existing concrete structures and testing their respective properties.

ASTM C138 - Standard Test Method for Density (Unit Weight), Yield, and Air Content of Concrete

- This testing method shows how to determine the density of fresh concrete, and how to calculate the yield, cement and air content of the concrete.

ASTM C143 - Standard Test Method for Slump of Hydraulic-Cement Concrete

- This test method covers determination of slump of hydraulic-cement concrete, both in the laboratory and in the field.

ASTM C192 - Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory

- This covers standardized requirements for preparing materials, mixing concrete, and curing concrete in the lab.

ASTM C231 - Standard Test Method for Air Content of Freshly Mixed Concrete by Pressure Method

- This test method covers the procedure of applying pressure to fresh concrete in specified chamber to measure the volume of air in the mix.

ASTM C494 - Standard Specification for Chemical Admixtures for Concrete

- This specification covers materials for use as chemical admixtures to be added to hydraulic-cement concrete mixtures in the field.

ASTM C642 – Standard Test Method for Density, Absorption, and Voids in Hardened Concrete

- This test method covers the procedure for testing hardened properties of concrete that are named in the description of the standard.

B. Electrical Engineering

AIEE 33 – Electrical Measuring Instruments

- This standard applies to numerous types of indicating electrical instruments for direct and alternating currents.

NFPA 70 – Standard for the Safe Installation of Electrical Wiring and Equipment

- This standard provides the latest requirements for safer and more effective electrical designs, installations, and inspections.

SAE J1939 – Standards for CAN BUS

- This is the recommended practice that is used for communications and diagnostics for vehicle components.

C. Mechanical Engineering

NFPA/T2.24.2 R1-2008 (R2017) – Hydraulic Fluid Power Systems

- This is a method for preventing external leakage to the system.

NFPA/T3.20.15-1990 (R2016) – Hydraulic Fluid Power

- This is a method utilizing quick action coupling – flush face type.

NFPA/T3.5.1 R2-2002 (R2015) – Hydraulic Fluid Power

- This is a method utilizing valves – mounting surfaces.

VI. Project Constraints

The team's main constraint was utilizing a maximum nominal aggregate size of 1-inch as well as printing around rebar. In the industry, 3-dimensional printing has only incorporated mortar mixtures or mixtures without coarse aggregate. Utilizing coarse aggregate causes more problems with pumping pressures and workability; however, it is vital in terms of sustainability and economy. Coarse aggregates were also used for dimensional stability in the concrete mixture. Also, the rebar is necessary for tensile reinforcement which required consolidation in order to allow the concrete to form around the rebar properly.

Another main constraint for the entire group was the abruptness of the skid steer turns. Being that the electricals did not have time to focus on creating a controlling arm for the print this semester, this was a drastic problem in producing a sinusoidal wall. This constraint will most likely be overcome in future semesters as ZARP decided to focus on a straight wall with no formwork which was approved by the project advisors. This approval was based on the lack of mechanical progress last semester that prohibited some forward progression this semester.

The civil engineers' primary constraints were utilizing the 1" aggregate size, creating a concrete mixture that was more than capable of holding its' edge, and being able to provide a consolidation technique that ensures proper formation around the rebar. The use of coarse aggregates with the 1" maximum nominal size meant that the system needed to incorporate a 4-inch diameter piping network. Also, being that the engineers wanted to produce a wall without formwork, the mixture had to be able to hold its' edge, or the concrete would not be able to form a wall. The concrete needed to be capable of holding its shape after vibrations were applied to it. The engineers working on the project last semester were able to produce a mixture capable of holding the edge, however, that was with formwork on three sides. Doing so without formwork could require a movable form that has a vibration attachment allowing the concrete to be consolidated as it is placed.

The vibration system was the primary focus of the civil engineers this semester. The frequency at which it operated was investigated with respect to the mixture design. Depending on how the mixture responded to a moving vibration plate, the frequency or the mixture design needed to be altered. With this said, the time it took for the mechanicals to deliver a working system was a constraint to the civils being able to alter the design that is necessary for success.

A major constraint the civil group felt was pertinent, but not necessarily stated in the project, was to ensure the mixture was sustainable in every way. ZARP wanted to make sure everything that was used in the design was economically feasible and environmentally friendly as possible.

The mechanical engineers had their own set of constraints as well. Having to use the 1-inch aggregate size correlated to using a 4-inch diameter piping network which brought into focus the pumping pressure problem. If a ¾ - inch aggregate would have been found and utilized, the piping network would still have needed to be 4 inches. The mechanicals were tasked with delivering the concrete mixture supplied by the civils. Using this size piping network constrained them to use a certain power motor and a certain length of piping network. The motor to the auger provided from last semester's mechanicals was not able to offer enough power, therefore, they first had to focus on finding the torque required to deliver the concrete. After they sorted that out, the mechanicals put their focus towards attaching the hopper to the skid steer. Being that the skid steer is a must of this project, the mechanicals were constrained to utilizing hydraulic power from the skid steer as there are not regular electric plug ins available in the field. This was a change for the mechanicals due to the last semester's system utilizing an electric power source. Also, the skid steer was not to be taken out of commission, so they were tasked with making the hopper be an attachment rather than welding it on to the skid steer front end. The skid steer was not able to be taken out of commission as it was used every day at Bert Cooper Laboratory and needed to remain operational.

The electrical engineers' constraints revolved solely around their software and the hardware of the skid steer. Being that the skid steer was used every day at the lab, the electricals were only able to sort through code in the evenings. Also, the manufacturer of the skid steer was not able to be cooperative in terms of allowing them access to certain coding data. This means they were constrained to using their own software to "sniff" out the codes necessary to convert the skid steer to be able to be controlled autonomously. "Sniffing" data refers to running numerous lines of code to figure out which line of code correlates to which aspect of the machinery. This was a major time constraint for this group as there were thousands of codes being sent through the skid steer.

Being part of an interdisciplinary team presented its own challenges as well. Communication amongst three different groups of engineers had its own obstacles to overcome along with finding time to meet and properly go over all pertinent details. The electrical engineers job really depended on the mechanical engineer's design while the mechanical engineer's job highly depended on the mixture design from the civil engineers. This constraint was overcome with effective communication between the groups.

VII. Summary of Data Gathered and Analyzed

The work of the previous semester's groups targeted creating a pumpable system that was moveable via crane. The concrete mixture design that was to be created needed to be capable of holding its shape as well as providing a workable surface. The crane and the pumping system ended up not working last semester, therefore, this semester's scope changed for the overall project. The pumping system was to become operational, and it was to be mounted to a skid steer in hopes that it could be used in the field wherever and whenever necessary. In the subsections below, each group's data, progress, and end-goals are elaborated on.

A. Civil Engineering Data

From the previous semester, a mixture design capable of holding its' edge was created. Because it was not actually able to be "printed" due to mechanical failures, the mixture design was essentially the same for this semester. Had the wall been able to be printed, ZARP would have worked on creating a more optimized mixture based on properties that allow for it be more cooperative with the overall system. There was still much room for improvement and work to be done by the civil group. Looking at the wall from last year, it was evident that there was a need for an effective consolidation technique.

From Figure VI.I, visual evidence existed of the layers not being cohesive as well as large voids where the rebar is located. This was the back side of the wall which was the side the form was placed. With this known, ZARP believed that a consolidation technique was necessary for the following three main reasons: consolidation would allow the rebar and concrete to become cohesive, it would allow for improved workability which would lead to pleasing aesthetics on each side of the wall, and consolidation would help increase the strength of the in-place concrete.

Figure VII.A.I: Back side of Fall 2019 Concrete Wall

Coring and Testing Data (ASTM C642 Problems)

To help illustrate the need for consolidation, cores were taken from the wall created in Fall 2019. Last semester, the concrete mixture that was used in the wall was also cast into cylinders and consolidated. These cylinders had a 28-day compressive strength of approximately 7800 psi which was an impressive design strength. Compressive strength is not what makes concrete great as there are numerous aspects; however, it is still a component worth testing to investigate.

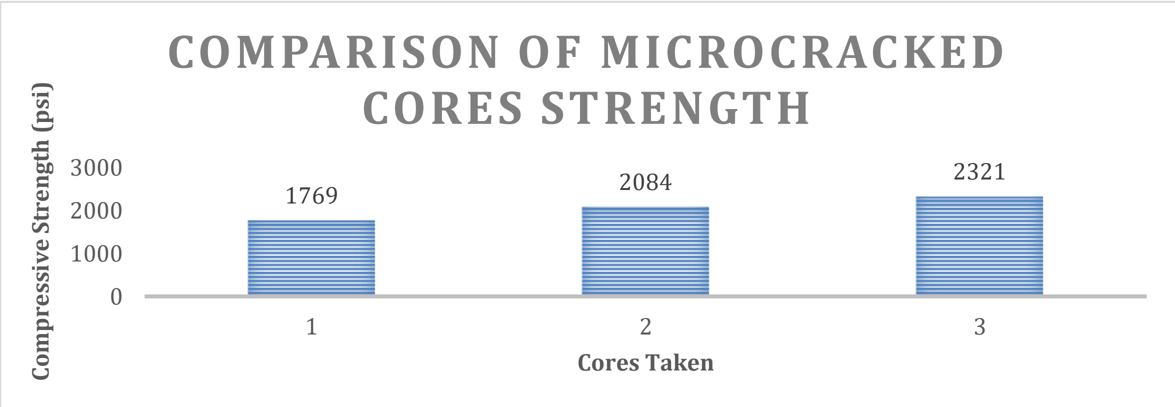


Figure VII.A.II: Comparison of Strength in Cores Extracted (Microcracked)

Initially, after taking cores of the in-place wall created last semester, ZARP believed the in-place compressive strength to be approximately 2000 psi. The difference between the in-place wall strength and the design strength values was significant indicating a possible need for consolidation or curing. The strength data for the cores taken can be seen above. However, this data was accumulated using ASTM C642. This standard is great for determining density and absorption values, however, ZARP realized that because this standard required oven-drying the cores, the strength values were skewed. Oven-drying the cores caused microcracking throughout which lead to loss of strength in the material.

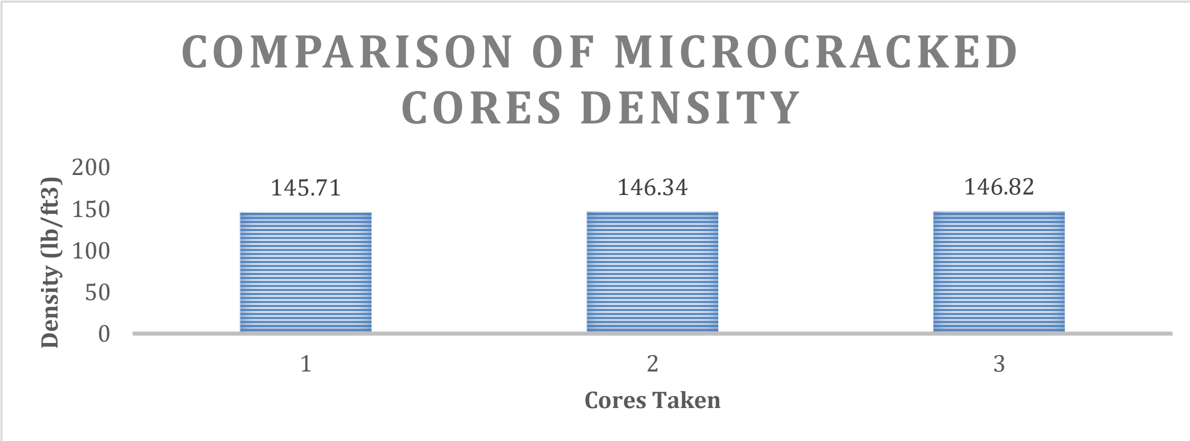


Figure VII.A.III: Comparison of Density in Cores Extracted (Microcracked)

Looking at the two charts from above, the higher compressive strength correlated to the higher density which makes logical sense. The problem ZARP was having is that the density is well within the normal range of 140 – 150 pcf while the compressive strength was resembling a much lower value. Due to following ASTM C642, ZARP believes there was a need to redo coring. This standard requires oven-drying which micro cracks the cores resulting in skewed strength values. The cores that were extracted next all underwent compression and density tests that did not require an oven as will be shown in the overview section directly below.

Coring and Testing Data (Overview)

After realizing ASTM C642 was not appropriate for density testing if followed by compressive strength testing, ZARP decided to pursue a simpler but informative route. The method ZARP utilized for the rest of the cores is shown below.

1. After coring, the cores were immediately grinded on both ends to ensure the core had no jagged ends. Ends that are not smooth can cause eccentricities and give improper breaks as well as skewed strength values.
2. After grinding, the cores were placed in the fog room in a bucket of regular water. They were placed here for seven days to ensure proper saturation.
3. After saturation, the cores were taken out of the fog room, patted down to SSD, measured for length and diameter, and finally weighed.
4. Finally, the cores underwent compressive strength testing according to ASTM C39. The loading applied was recorded.

5. Based on the average length and diameter as well as the weight, density was calculated by weight / volume of a cylinder. Lastly, the compressive strength was calculated by the loading applied / cross-sectional area.
6. If the length to diameter ratio is not 2:1, refer to ASTM C42 for the proper correction factors needed to be applied to the compressive strength values.

The rest of the cores taken this semester consisted of re-coring the previous semester's wall, coring the dual extruded wall, and coring a control wall that was created all in accordance with the method previously shown. Each of these values are shown below in Figure VI.A.IV and Figure VI.A.V.

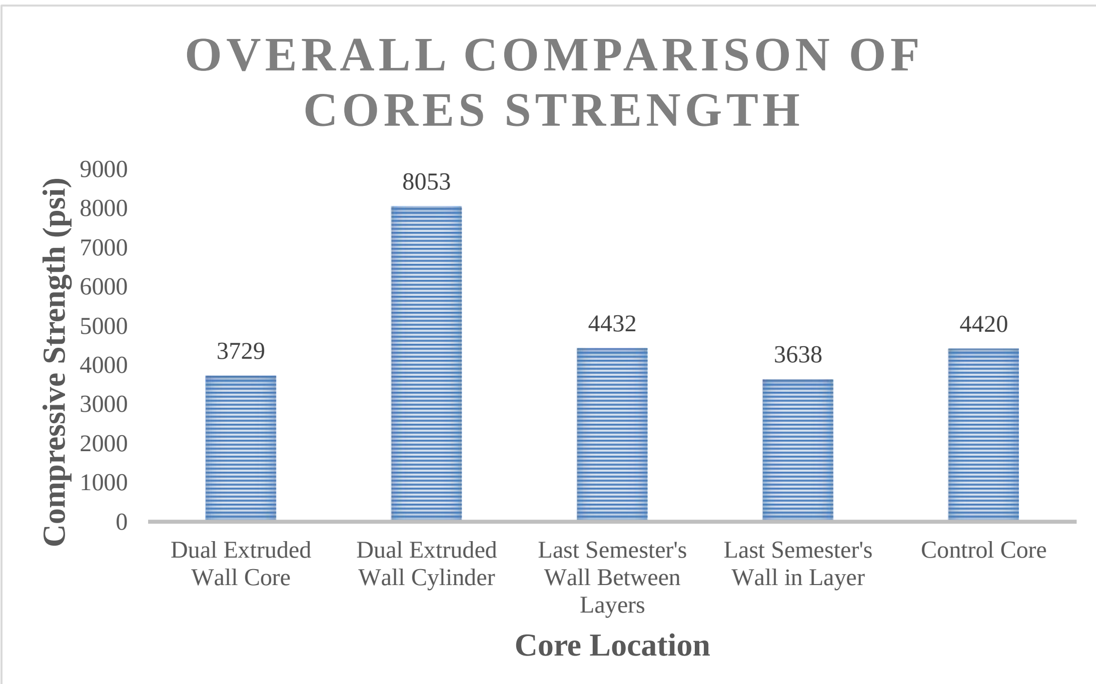


Figure VII.A.IV: Comparison of Overall Strength in Cores Extracted

As shown in the figure above, there are significant differences between the dual extruded wall control cylinder and the in-place cores. The control cylinder is almost the same as the control cylinder from the previous semester's mix. As can be seen, there are differences in strength of in one layer versus between two layers. Also, there are differences between the method of placing the wall. The Control Core shown in the figure above as well as the following figures was a core taken from a box that was properly consolidated. The Control Core was supposed to give ZARP an idea of in place strength and density of the mix design without defects from printing. It is hard to conclude any firm results from the number of cores ZARP took this semester. With this known, please see the Next Steps section to see how to further the progression of this project.

While the dual extruded wall core was between the two taken from last semester's wall, it was evident that there was insufficient evidence to tell which method was better. However, the dual extruded wall did allow for more cohesion to the rebar and a more controlled print which were some of the leading reasons to promote this method.

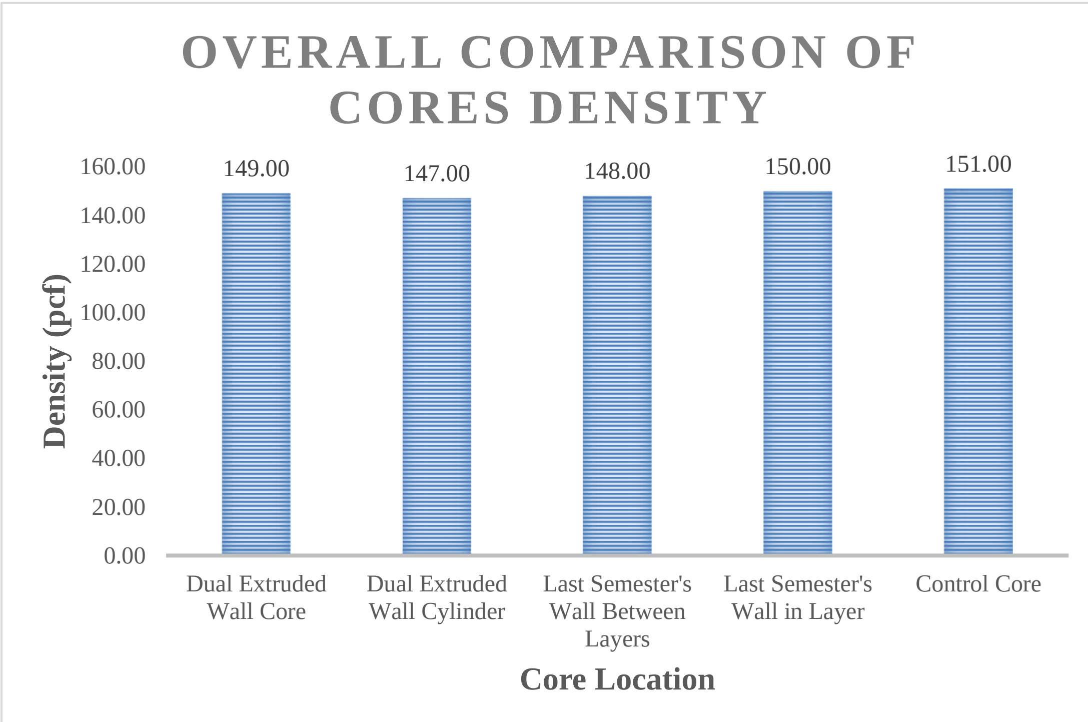


Figure VII.A.V: Comparison of Overall Density in Cores Extracted

Shown in the figure above, it is evident there are only slight differences in density which allows ZARP to believe density is of no concern. Most of the values are within the industry respected range of 140 – 150 pcf. Due to the new method, as stated above, which was used to conduct density testing, the densities are slightly larger than expected because of the cores being completely saturated. While the graph shows differences, the differences are extremely minute and are all well respected.

Coring and Testing Data (Dual Extrusion Wall)

ZARP truly believed dual extrusion was the future of 3-D concrete printing. Therefore, a wall was created attempting this method. As shown in the previous section, density was not a problem for any method. While the dual extruded core did not necessarily provide great insight into how effective it could be, the strength was still competing with that of the single extruded wall. There was not much additional data to analyze, but the Next Steps section will give advice on how to further the progression of this method.

The dual extrusion setup can be seen in Appendix C. This appendix will state the components necessary as well as the procedure to follow.

Vibration Information / Curing Information

This semester, three vibration methods were experimented. These consisted of vibration applied to the rebar, parallel to the sliding plate (backform), and perpendicular to the plate (backform). Each of these methods can be further seen in the Alternatives Analysis section which elaborates on the method and the results for each. It was evident the vibration needed to be applied perpendicular to the formwork. There was no real data to support this. This was based on visual evidence shown in the Alternatives Analysis section.

This semester, to help aid in strength gain and minimizing pore spacing, curing was investigated. Because the end-goal was to create a vertical structure, pulp cure was the method of choice. While there was a wall created with pulp cure applied, there has been no data collected at this time. The future of experimenting the curing method and its effects will be shown in the Next Steps section.

B. Electrical Engineering Data

This semester, having the hopper system being mounted to a skid steer and controlled autonomously, correlated to a complete redesign by the electrical group. The electrical engineers have "sniffed" out data to figure out what code correlates to which aspect of the skid steer. Again, "sniffing" data refers to running code and analyzing which line of code correlates to which aspect of the machinery. This can be visualized in the figure below.

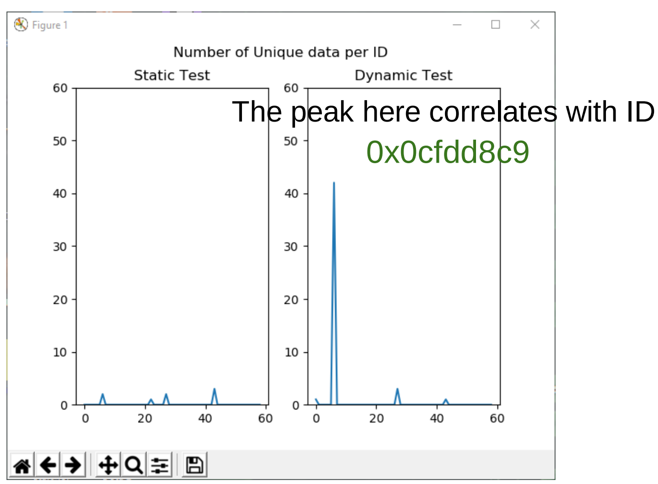


Figure VII.B.I: Code "Sniffing"

Looking at the figure above, the ID "sniffed" out coincides with a forward movement of the skid steer. The static test is nothing being performed, and so when the dynamic test is enacted then a code is visualized for each movement or control being operated. This process was done to figure out what controls the aspects that ZARP needs from the skid steer. The electrical group did a lot of data collection and analyzation with this same method. They utilized lidar sensors to map location; however, this data has not been collected yet. Also, they oversaw creating the control box and communication with the vehicle which can be further illustrated in the Alternative's Analysis and Selected Approach.

C. Mechanical Engineering Data

The mechanical group focused on making the hopper system operational, fabrication of numerous items, and procuring a method to attach the hopper to the skid steer. In terms of making the system operational, it was evident from trials that the motor supplying power to the auger was extremely weak. In fact, the torque being supplied by the motor was a mere 48 lb-ft. To figure out how much torque was required, the mechanicals decided to perform a torque wrench test on the auger while concrete was halfway filled in the hopper. This torque came out to approximately 130 lb–ft for consistent motion. The mechanicals want to extend the auger casing and length of the auger, but there was no data to support this claim.

Figure VII.C.I: Torque Test

The mechanical engineers also worked on the analysis of the consolidation system in terms of forces that it could withstand. It was found that the design of the consolidation system could withstand 284.2 lbs in line with the hopper, that is concrete pressure against it. The consolidation system was also found to be able to withstand 201.7 lbs laterally as a type of shear force when the consolidation system moves with the system during printing.

VIII. Alternatives Analysis

This design project was more like an iterative research project. There could be additions to these alternatives that have not been thought of. ZARP was working on several different aspects this semester as will be shown in the sections below. The civil group primarily focused on the mixture design and consolidation method. The mechanical and electrical groups will have their alternatives shown in the overall delivery method.

A. Mixture Design Progress Towards Optimization

Last semester, a mixture design was created that allowed for the creation of a three foot by five foot by eight-inch wall. While this mixture design is far from optimized, the altering of it may have to wait. Because the mechanical group has failed to produce a working pump or "printer", there was no evidence that supported altering the mixture design in terms of cooperation with the overall system. The mixture design contained the following components: 3/8" coarse aggregate, 1" maximum nominal aggregate size coarse aggregate, fine aggregate, cement, fly ash, water, Daracem 55, citric acid, and nano-clays. Each of these components served a specific purpose. The coarse aggregate helped take up space in the mixture to save on cost and provide structural stability. The different sizes of aggregates lead to a more cohesive mixture based on aggregate gradation. Cement and water were essential components, but the 20% fly ash replacement was necessary to help with cost and workability. Daracem 55, a midrange water reducer, allowed for ZARP to utilize a lower water to cement ratio while keeping the mixture flowable. The citric acid does numerous unknown things, but it primarily helped maintain the slump for a longer period. Lastly, the nano-clays allowed for the mix to stiffen up when energy ceased to be applied. The mixture design was created using the tarantula curve. This curve and its' excel sheet were created by Dr. Tyler Ley and taught to the ZARP team during concrete mixture design.

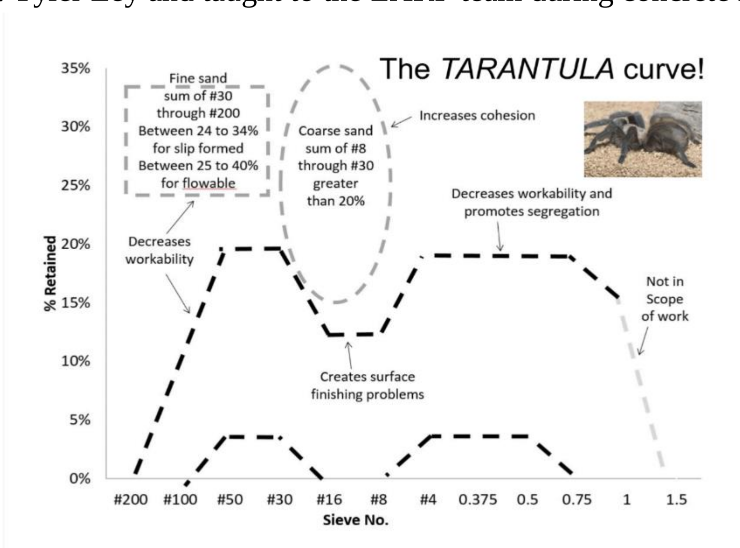


Figure VIII.A.I: Tarantula Curve

Once the system is working, the civil group will be able to alter the mix based on cooperation with the overall system. After this is done, aspects can start being altered to better suit sustainability in every way. The alterations will work accordingly with the tarantula curve in order to produce an optimum aggregate gradation. This is a research process that would not benefit from an analysis between every component at this time.

B. Consolidation Method

Like with the mixture design, this was also an iterative process. The need for consolidation was to help with the exterior aesthetics of the in-place wall, add to the strength of the wall, and allow for the rebar to be cohesive with the concrete to ensure tensile reinforcement was properly utilized. To figure out which method worked best, ZARP ran through numerous trials of testing while using the same mixture design. ZARP first based the analysis off aesthetics because of the following reasons: strength can always be overcome, and if aesthetics are good that means exterior pitting is minimal, leading to more protection of the rebar. Also, if aesthetics were good, that would have given a positive sign of the rebar being more cohesive with the mixture as it would have appeared more workable. The analysis can be shown below in Table VII.B.I. The scale of 1 to 5, 1 being the worst and 5 being the best, was utilized for the decision matrix.

Table VIII.B.I: Consolidation Technique Decision Process

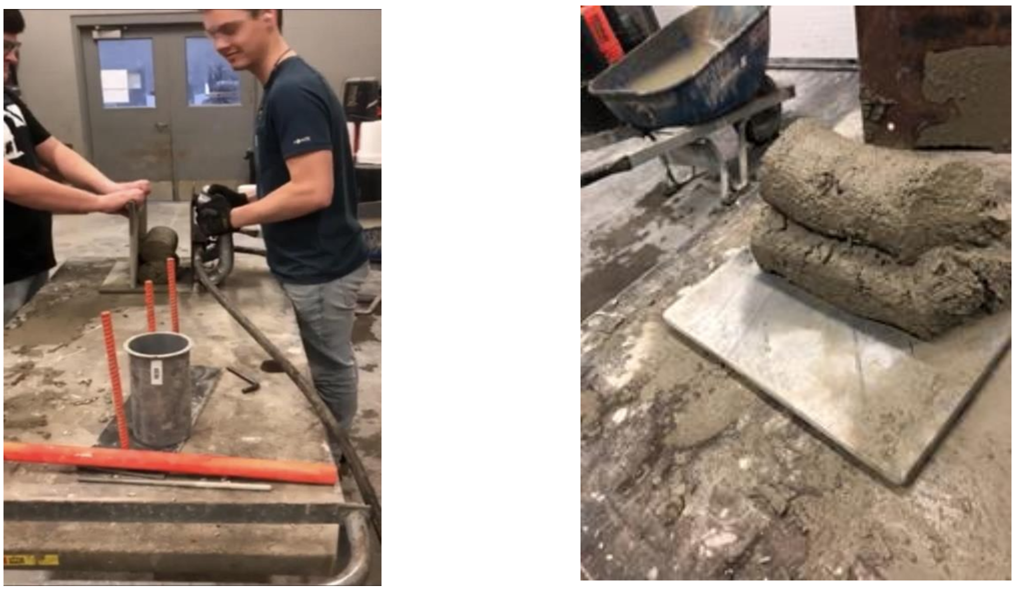
Consolidation Technique Analysis (1 to 5)					
Method	**Aesthetics**	**Effectiveness**	**Attainable**	**Team Approval**	**Total**
Vibration Parallel to Traveling Plate	2	1	5	3	11
Vibration Perpendicular to Traveling Plate	4	5	5	5	**19**
Vibration to Tensile Reinforcement (Rebar)	3	3	3	1	10

After basing the analysis on aesthetics and team approval, the team further analyzed the methods based on the effectiveness with vibration and how attainable it was to attach the method to the overall system.

Originally, ZARP was going to judge the methods on density and strength instead of effectiveness and attainability. In order to get the true in-place strength, the wall needed to be cored in different locations and then tested for density and strength per their respective ASTM standards. While these were vital to the properties of the wall and to the engineer's design, the team moved forward with the method highlighted above. The density, ZARP felt, was not going to be a problem. If the strength was a problem in the wall, the engineer could always use a wider cross-sectional area. The three methods will be elaborated on in their respected subsection below.

Vibration Parallel to Traveling Plate

This method was simple and like that of the next method. There was a plate on either side of the proposed wall thickness; in this case the distance between would be 8 inches. A vibrator, or stinger at this point in the research, was applied parallel to the plate. Using the vibration parallel to the plate, or the traveling form, the consolidation was quite poor. This was due to the oscillation of the stinger vibrator used. The oscillation of the stinger in this direction did not propagate the waves towards the heart over the wall. It propagated away from it hence there was minimal consolidation occurring. The figure below represents the method and the outcome with respect to aesthetics.



(a) Method (b) Results

Figure VIII.B.I: Vibration Parallel to Traveling Plate

As shown above, this method hardly consolidated and offered little to no help in achieving pleasing aesthetics. The density and compressive strength should be acquired in the future from testing cores of this type of consolidation method. The team approved of it because it was still more effective than doing nothing, and it fit in how the mechanicals wanted to combine the consolidation method with their system.

Vibration Perpendicular to Traveling Plate

This method was almost the same as the vibration parallel to the traveling plate. The major difference being the stinger vibrator was applied perpendicular to the plate in order to allow the oscillations to be propagated into the heart to the concrete effectively. The figure below represents the method and the outcome with respect to aesthetics.

(a) Method (b) Results

Figure VIII.B.II: Vibration Perpendicular to Traveling Plate

As shown above, this method effectively consolidated and somewhat achieved pleasing aesthetics through workability. The team highly approved of this as it offered promise in terms of consolidation and fit into the end-goal system. With an extra pass or two of the traveling form, the exterior should reach the aesthetics desired.

Vibration Applied to Rebar

This method was simply applying the stinger vibrator to the rebar that was essentially in the middle of the wall. This method worked well but also too intense. It collapsed the bottom of the wall extremely quickly, most likely because the bottom metal plate carried vibration, as can be shown in the figure below.

(a) Method (b) Results

Figure VIII.B.III: Vibration Applied to Rebar

As shown above, this method over-consolidated the mixture. It had a low team approval based on how it would be applied in the field. The other methods can be attached to the system while this one would have to be operated separately. ZARP rated it decent on aesthetics as it did provide a smoother exterior, but it was simply too intense. More testing without the metal plate on bottom could lead to different results. However, having a method that can vibrate as the overall system moves works to the advantage of the contractor.

C. Curing Method

Curing is one of the most important aspects with concrete that is generally overlooked. It allows for the continued hydration of concrete which allows for strength gain and minimizing pore spacing. There are many methods of curing such as the no-cure, spraying water for a period of time, and applying wet burlap to the surface. These curing methods are applied after initial set and can be applied for differing amounts of time based on investigation. One newer method, pulp cure is simply shredded newspaper, water, and sometimes added "spices" to increase effectiveness. "Spices" refer to a tackifier which increase cohesiveness of the pulp.

Table VIII.C.I: Curing Method Decision Process

Delivery Method Analysis (1 to 5)					
Method	**Ease of Use**	**Effectiveness**	**Attainable**	**Team Approval**	**Total**
No Cure	5	1	5	2	13
Wet Burlap	1	1	1	1	4
Spraying Water	5	5	2	2	14
Pulp Cure	4	5	5	5	**19**

No Cure

This method of curing was what had been utilized in previous semesters. As the name states, this method is simply leaving the concrete be after placing it and applying no additional water to allow it to cure. However, the strength of the in-place concrete was not up to adequate standards.

Because it has been proven that curing can lead to strength gain, this method was not ideal for the future of 3-D printing concrete.

Wet Burlap

This method of curing is very common in industry. It is simply wetting down burlap which is known to hold water well. Once the burlap is wet, apply it to the surface and allow the gravity to cooperate with the burlap in keeping water constantly in contact with the concrete surface. However, this project is focusing on building vertical structures. Burlap was unable to be applied to vertical structures which results in the very low scores as it was not applicable for ZARP's needs.

Spraying Water

Spraying water on the surface is effective and easy, but no one in industry wants to continuously spray water for hours on end. This method was very easy and attainable; however it was not adequate for this project. For vertical structures, the water would have to be running non-stop which would lead to sustainability issues. Spraying water works for horizontal surfaces as the water can "pond" on the surface for a short time before being applied again.

ZARP decided the waste of water from this method is unnecessary when there was a better option available as shown below.

Pulp Cure

This method of curing is very simple. While it is new to industry, anyone is capable of learning how to apply it. The basics of pulp cure is shredded newspaper blended with water. There can be added "spices", tackifier, that allowed more adhesiveness. However, the water and newspaper has shown to be adequate in terms of retaining water and staying attached to the vertical surface.

Pulp cure was easy to apply, has been effective as shown through research, was easily attainable, and the team feels was the best method to go with. While there are machines to apply pulp cure, they often have to have a low impact angle, which was unattainable when the pulp cure wall was made, however pulp cure was a great option for vertical surfaces. Lastly, pulp cure was arguably sustainable as it is biodegradable.

D. Overall Delivery Method

Now that the alternatives for the civil side of the project have been discussed, here are some methods of delivering the concrete. Because this hopper and auger system did not work in the past, ZARP worked towards improving it and moving forward in a simple manner. The mechanicals did not want to over complicate any aspect because they realized the only way to progress this overall project was to first see how the extrusion system worked and can be improved. The table below will elaborate on the difficulty to use this system, the effectiveness of it, if it was an attainable goal this semester, and the team approval.

Table VIII.D.I: Delivery Method Decision Process

Delivery Method Analysis (1 to 5)					
Method	**Ease of Use**	**Effectiveness**	**Attainable**	**Team Approval**	**Total**
Dual Extrusion	1	5	2	2	10
Single Extrusion *(With Traveling Backform)*	4	2	4	3	13
Single Extrusion *(With Traveling Vibrating Backform)*	4	4	4	5	**17**

The civil engineers believed the dual extrusion method is the future of 3D printing concrete. However, because there was not already a working system, the overall group decided against it. This method required more work in the piping system or possibly moving arms electronically. Therefore, with wanting to have a traveling form to eliminate permanent formwork, ZARP had the option to do it with or without consolidation. The civil group believed consolidation is a necessity. The vibration was incorporated in the selected approach on either one or both sides of the traveling formwork as can be seen in the next section. The methods shown above will be explained in three subsections below.

Dual Extrusion

Dual extrusion was a method that the civil engineers felt will be the future of the 3D concrete printing world. Instead of only printing from one nozzle, it would allow printing from both sides of the wall. This could possibly eliminate the need for excessive consolidation as the rebar would be forced between the two layers helping it become more cohesive. Also, the mix would not have to flow as far laterally which correlates to being able to have a stiffer mixture, but not stiff enough to cause pumping pressures or other mechanical problems. This is great because it would decrease time between laying the layers which would save even more money in industry.

This method could be managed with the use of two extrusion pipes or moveable arms off the system. ZARP has done a demonstration of this method earlier this semester. It gives signs of consolidation naturally through forcing the layers together. It would allow for a quicker, more effective print.

It was not feasible this semester for reasons as stated earlier. Therefore, the team approval and attainable categories are rated so poorly. However, ZARP would like future groups to take a dedicated look into this approach.

Single Extrusion with Traveling Backform

This method was having a traveling backform to move with the system to help eliminate the need for permanent formwork. It can be visualized in the Selected Approach. The main idea behind this was to allow the extrusion of the concrete to occur simultaneously as a form is moved alongside it to finish the exterior. The problems this faced was that the mix was stiff enough to where it needed more energy than simply finishing it. This was where vibration came into effect. For these reasons, it was rated close to the category following this one, however, it was poorer in effectiveness and therefore overall team approval.

Single Extrusion with Traveling Vibrating Backform

This method was single extrusion with a traveling backform. The difference being that there was a vibrator placed on the backform to propel energy to the concrete in order to consolidate and help with finishing. For these reasons, it was ranked the highest of the methods. This method is elaborated on in the selected approach through visual aid. It should be noted that this method, while showing promise, will need research to determine an optimum frequency to run the vibration at. Also, longevity of vibration will also be a factor that needs to be investigated.

Other Mechanical and Electrical Analysis

The mechanicals also had to do an analysis on the power to their system. The original system utilized electric power, but that was simply not feasible in the field. Also, the electric motor in the system only put out 58 lb-ft of torque. Therefore, they would either use a power pack or utilize the hydraulic power from the skid steer. This was to be determined based on their knowledge and understanding of hydraulic systems. It was not feasible for them to develop a system without the power pack that they felt was much easier to utilize in the time allotted.

In terms of the electrical group's work, there were not many methods for the groups to analyze. They had debated which Arduino system to use as well as if they should get a different or keep the same Lidar sensor from last semester. There was really no background to their analysis other than they felt they could work effectively with what they had at hand. The electrical components will be elaborated in the selected approach.

IX. Description of Selected Approach

ZARP was aiming for a consolidation method that would yield a density of approximately 145 pcf, a compressive strength of 4000 psi or higher, and pleasing aesthetics of a finished wall on both sides. Also, the overall group wanted to create an autonomous system that would allow for the creation of a 3-foot-tall, 5-foot-long, 8-inch-wide wall without permanent formwork. The consolidation method utilized was going to be vibration on the traveling form. This can be seen in the figure below. What is not seen, is there was also be a plate attached to the pipe that the concrete flows through in order to smooth and vibrate that side of the wall as well. The vibrators would utilize power from the skid steer while the mechanical system would use a power pack.

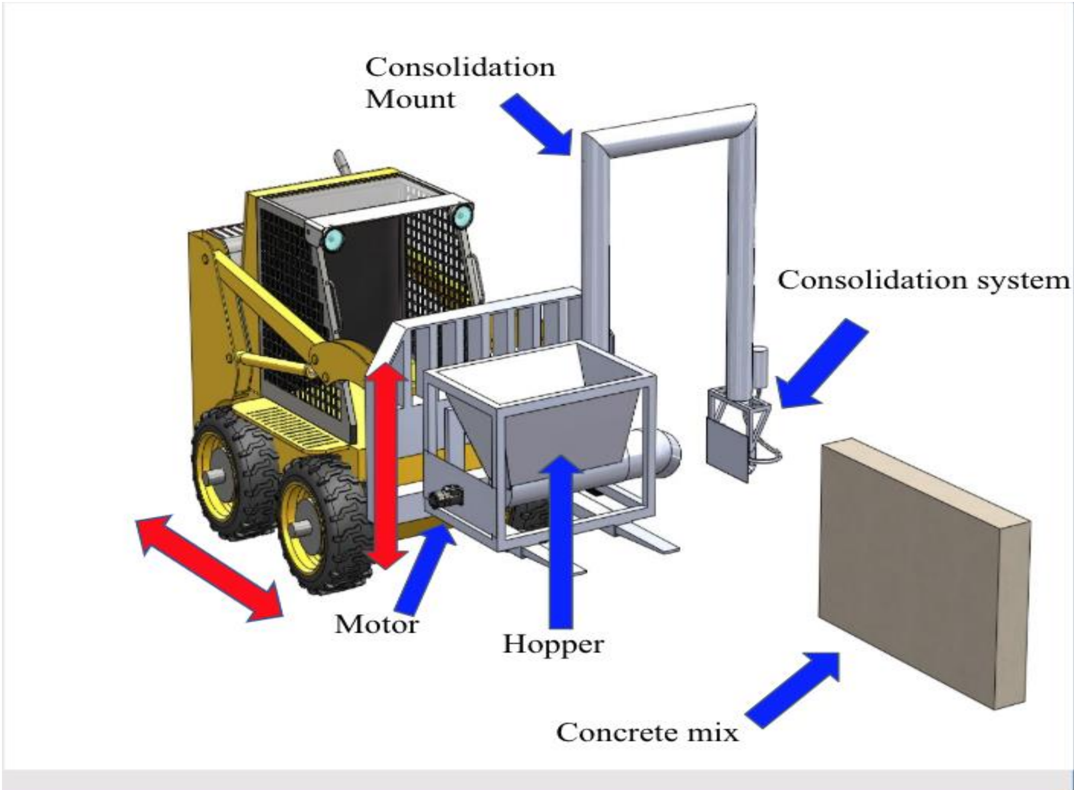


Figure IX.I: Overview of Selected Approach

In short, the system would be as follows. The hopper system would be mounted to the skid steer. The power would be supplied from a hydraulic power pack to the motor and in turn to the auger system. The mounted consolidation system would move as the skid steer moved in order to finish the concrete as it was placed. The consolidation mechanism, or vibrator, would be supplied with hydraulic power from the skid steer. It would be operated at a frequency determined by the civil engineers through research. The plates, on each side of the consolidation system, would finish and consolidate the wall thoroughly. However, caution was needed to not over consolidate because the wall needed to maintain a certain stiffness in order to allow the next layer to be placed without lateral displacement of the layer's underneath. Overall, ZARP felt this was a great approach moving forward. There could be alterations once the mechanicals get the system up and running depending on several variables.

The electrical group's components can be seen in Figure VIII.II. The primary controller would be responsible for controlling and localizing the skid steer. It would connect to the CAN bus and control the skid steer by sending the operation codes. This controller would receive information from three Lidar sensors and act upon them to keep the integrity of the print. This information as well as a camera view of the extrusion point would be displayed on a monitor in the cockpit so that an operator could make sure the print was going smoothly and make any adjustments if necessary. The operator would also need to take control during the reload process.

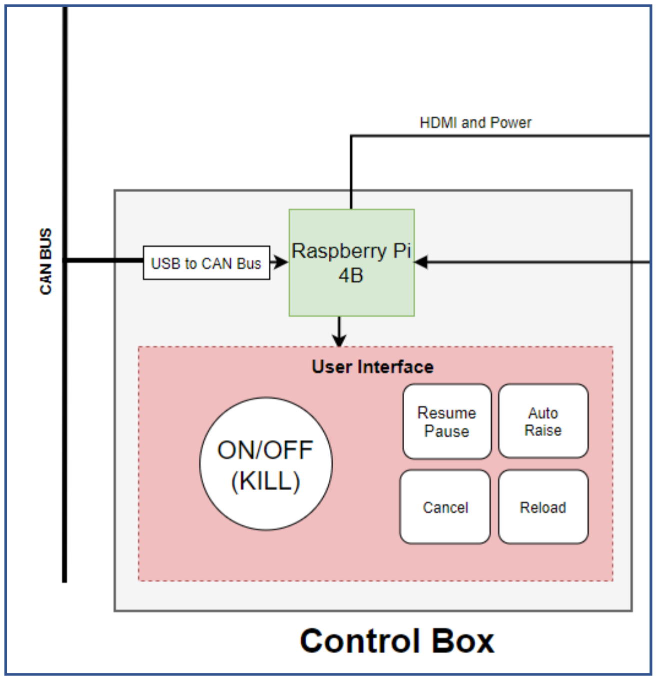


Figure IX.II: Electrical Control Box

This was the selected approach. It was subject to alterations should anything go wrong with any of the subgroups' systems. Each system is further detailed in the subsections below.

A. Mechanical System

The mechanical system was made up of the skid steer, hopper system, and the dispensing system. The hopper/auger would be lined with a clear coat to prevent concrete from sticking to it. The hopper would then be mounted to the fork attachment of the skid steer. The skid steer would drive forward and backwards as the hopper extruded concrete to print each layer and the skid steer would also move the hopper up to add more layers to the wall and down to refill the hopper. The auger blade inside of the hopper would force the concrete into the dispensing system which would then extrude the concrete to form the wall. The dispensing system included a traveling form that was positioned on the backside of the wall as it was being printed that was equipped with a vibrator to add a smooth finish to the wall and aid with consolidation. After each mix ran through the system, the hopper/auger must have been sprayed down and cleaned to ensure product life was maximized and prevent buildup in the system. If a job must stop mid print, the concrete could be kept from stiffening by agitating the mix with a Minnich concrete vibrator.

B. Electrical Control System

The control system consisted of both hardware and software elements. The hardware would use a Raspberry Pi, an Arduino Uno, three LIDAR sensors, two rotary encoders, automotive buttons, and a kill switch. The software included python code that would communicate wall specifications to the control unit, and Arduino code to run the operation of the skid steer and sensors. The Raspberry Pi would be taped into the Controller Area Network (CAN bus) of the skid steer and would act as another control unit in the system that can send CAN messages across the bus, causing the required movements of the skid steer and loader arm. The Arduino would control and monitor the sensors and relay this information to the control box connected to the bus. The control units would be powered by a 12V outlet from the battery in the skid steer. A buck converter would step down the voltage to 5V which was the operating voltage for the RPi/Arduino. It also protected the system from voltage spikes. A fuse would be used to prevent too much current in case of a short. Since ZARP was trying to electrically operate the vehicle, several safety measures would be in place. During testing, a certified skid steer operator would sit in the cockpit with a kill switch to the Control System. This operator would have been able to shut down messages sent to the bus and take over manual operation at any time. Testing would be done in a roped off location outside of the lab. The final design also included proximity sensors to prevent any collisions.

C. Civil Engineering Components

Mixture Design

The mixture design utilized was the same as last semester. The design was composed of:

- 1" Maximum Nominal Aggregate Size Coarse Aggregate
- 3/8" Coarse Aggregate
- Fine Aggregate
- Water
- Cement
- 20% Fly Ash Replacement of Cementitious Materials
- Citric Acid
- Daracem 55
- Nano-Clays (Wet or Dry)

The amounts varied based on aggregate gradation. The one constant was that of the cementitious material, twenty percent was replaced with fly ash. A water to cement ratio of 0.40 was utilized for this mixture design.

Vibration Method

Based on the three methods that were tested with, ZARP decided to pursue applying vibration perpendicular to the traveling form. This method still needs to be further investigated as a stinger vibrator, which was how ZARP performed testing, will not be the vibrator utilized in the finished system. As shown in the overview of the selected approach, vibration was to be applied on both sides of the traveling form. This was to allow the vibration frequency to still be mild despite having an eight-inch wall thickness.

It should be noted that the Next Steps section will give detail how to further progress this approach. Due to COVID – 19, a final working system was not able to be created thus causing vibration to not be finalized.

Curing Method

The civil engineers on this project believed curing would allow the strength to increase enough in order to give the wall proper strength with respect to industry standards. This project was to create vertical structures; therefore, pulp curing was the method of choice. This method is simply newspaper, water, and a tackifier if needed to allow proper adhesion to the surface.

This semester, ZARP chose to only use shredded newspaper and water. It was applied in approximately ½" thickness to the wall by hand placement. There were 16 cylinders created, 8 to experience conditions of the pulp cure wall, and 8 to be placed in the fog room. No information was collected from these cylinders due to the pandemic restricting lab access.

Obviously, there is much to still be investigated, but due to COVID -19, the progress came to a stop. The Next Steps section will give advice on how to keep progressing this project.

X. Summary of Engineering Design and Analysis

This section is comprised of the overall engineering design procedure. Since this is a continuation research project, the design for this semester does not start at the beginning. The Fall 2019 semester's group developed a concrete mix design with the desired properties of being able to hold its shape and the layers being easily stackable. Last semester's group also developed a quick, simple test to evaluate those properties called the "Oopsie test". The Oopsie test procedure can be seen in Appendix C. The purpose was to simulate a small controlled version of printing concrete in place to visualize stiffness and measure how many layers could be stacked without deformations. Since the concrete mixture design was already created it gave ZARP the chance to focus on other civil aspects until the mechanical system was ready. The end-goal deliverable that ZARP wanted to produce this semester was a 3' x 5' x 8" concrete wall. The wall would be created without permanent formwork and would offer pleasing aesthetics on each side as well as in-place properties that are desired for industry purposes. In the subsections, each team's design procedure will be outlined in order to reach the end-goal.

A. Civil Design Aspects and Analysis

For the civil group, the end-goal was to create a concrete wall with or without a working mechanical system. In order to do this, excel was utilized with the Tarantula Curve to properly create a mixture based on aggregate gradations. While this mixture design had already been accomplished last semester, this curve was necessary to recreate the mix based on changing aggregate properties. The primary focus for this group was to effectively consolidate this mixture and find a way to incorporate consolidation into the overall system. This same mixture was constantly undergoing Oopsie tests alongside differing vibration techniques to find a proper consolidation method. Once this method was decided on, the frequency and longevity of the vibration was to be further investigated for optimization of the consolidation technique.

Furthermore, AutoCAD was going to be used to properly outline the base or “foundation” to print on that was forklift accessible. Also, this software would allow the civil engineers to detail the consolidation technique and each component of the system.

The civil engineers, if time allowed, were also going to attempt to optimize the mixture based on cooperativeness with the overall system. Once the mechanical engineers figured out a working system and were ready for trials, the civils could alter the mix design in terms of workability if needed. Also, once a mixture worked with the system, the civil engineers could focus on altering the mixture for sustainability purposes. This solely depended on when the mechanicals and electricals produced a working system. Therefore, this was not the main goal for the civils this semester.

Batch Values	Mix 1
Size	1.5
Cement (lb)	29.24
Fly Ash (lb)	7.31
SCM 2 (lb)	0.00
Coarse Agg 1 (lb)	73.61
Coarse Agg 2 (lb)	22.22
Coarse Agg 3 (lb)	0.00
Fine Agg 1 (lb)	73.63
Fine Agg 2 (lb)	0.00
Water (lb)	13.56
Nanoclays (g)	63.05
Daracem (g)	220.67
0.25% Citric Acid (g)	41.45

Figure X.A.I: Mix Design Components

For the civils, calculations were limited. The only calculations necessary were finding the compressive strength and density of the cylinders and cores. The compressive strength was done by dividing the load applied by the cross-sectional area of the cylinder or core. The density was simply the SSD mass divided by the volume. There was a standard as well to follow in order to calculate density, but Dr. Ley wanted us to use the simplest method possible in order to help others around the world with simple testing methods.

- Compressive Strength = Load / Cross-sectional Area
- Density = Mass / Volume

Excel was also utilized in order to create a cost analysis for the materials and for the labor as will be shown in section XII.

B. Electrical Design Aspects and Analysis

The electrical group's primary focus was autonomously controlling the skid steer. They found the data from the skid steer to pinpoint which code correlates to specific movements/controls of the skid steer system. Once they found the pertinent codes, they were able to start set up on their automated system.

This system would utilize two controllers: a primary controller and a secondary controller. The primary controller would control and localize the skid steer. It would connect to the CAN bus and utilize the codes found in order to control the skid steer. The secondary controller would utilize the Lidar sensors in order to keep the integrity of the print. These Lidar sensors would be connected first through the Arduino system and then to the control box. These sensors would allow for ZARP to essentially create their own positioning system based on surroundings.

The electrical group used AutoCAD for design purposes as well as to create a model to 3D print a control box at Endeavor. For equations, the electricals did not utilize any that the team is aware of. Their project was similar to that of the civils in the respect of being more iterative research rather than a clear-cut design project.

This group also utilized excel for a cost analysis.

C. Mechanical Design Aspects and Analysis

The mechanical group's main task was to produce a working auger system capable of feeding the concrete supplied by the civil engineers. This system would be mounted to the skid steer and utilize the hydraulic power from the skid steer. If the mechanicals were unable to figure out the skid steer's power, then they would use a power pack to supply the system. However, a power pack was an extremely expensive option whenever free power was available from the skid steer.

To start this semester, the mechanicals first performed a torque test in order to determine they needed a much stronger motor to power the auger system. From this, they acknowledged the need for hydraulic power. Being unfamiliar with hydraulic power, they worked diligently on attempting to figure out how to connect their system to the skid steer, however, they were unable to completely figure it out.

This group utilized SolidWorks to design the overall system as shown previously in the report. AutoCAD was also utilized for differing parts of the system. As far as equations are concerned, the mechanicals did not find equations pertinent to many aspects of the project, but planned on trial and error. The following equations are what they planned to effectively use:

- Center of Gravity (To find how much counterweight is necessary)
- Volumetric Flow Rate (To find rate of concrete flow necessary)

They also used Excel to find stress and deflections from the consolidation mounting system in order to combat any foreseeable problems.

Once the system was fabricated and mounted to the skid steer, the mechanicals were going to oversee any troubleshooting with this system. Plenty of safety procedures were put in place in the Standard Operating Procedures in Appendix F.

Like with the other disciplines, excel was utilized to perform a cost analysis of their side of the project.

XI. Sustainability Analysis

A sustainability analysis was performed according to the Envision Checklist explained to ZARP earlier this semester. There were five categories to go through within excel. These categories are quality of life, leadership, resource allocation, natural world, and climate. Because a large amount of the items within these categories were not applicable, ZARP rated sustainability out of 532 points instead of the overall 1000. Therefore, ZARP solely determined the sustainability on the applicable topics as will be elaborated on in the upcoming sections.

ENVISION™

The summary of results for the Envision Rating can be quantified in the table shown directly below.

Table XI.I: Envision Rating Results

Category	Yes	No	N/A	Points Earned	Points Possible	Percent of Points Possible
Quality of Life	27	6	7	21	94	22%
Leadership	35	4	3	96	140	69%
Resource Allocation	14	7	3	21	148	14%
Natural World	5	1	11	7	32	22%
Climate	19	1	4	59	118	50%
TOTAL	100	19	28	204	532	38%
Envision Rating - SILVER						

A. Quality of Life

This section of the analysis was very prominent for the overall project. ZARP believed three of the categories that easily apply to this project were Enhance Public Health & Safety, Improve Construction Safety, and Minimize Noise & Vibration. ZARP felt that when creating homes for as cheap as possible, this would greatly enhance people's lives all over the world. Not only would people save money, but the less fortunate would be able to have shelter and a place to call home. Also, the next two categories somewhat coincided with one another. ZARP felt that having a standard operation manual was one way to improve the safety on construction sites. Also, this system would reduce the amount of manpower required. Therefore, the overall dangers posed to humans of being on any construction site are lowered dramatically. Lastly, utilizing one simple skid steer versus a whole crew of people and machinery to build a home would greatly minimize noise and vibration in ZARP's opinion.

Shown below, several other categories apply to this project. They were all accounted for based on the Envision Checklist according to their descriptions within the excel file. The reasoning for the lack of points for this category were based on a few "No's". Some topics did not allow for any "No's" in order to keep any points, therefore, ZARP lost some as a result of this process.

			Credit Assessment Status	Evaluation Questions Assessed		Assessment Status						Assessed Maximum Points Available	Total Maximum Points
				Yes	No	Improved	Enhanced	Superior	Conserving	Restorative	Points		
Quality of Life	Wellbeing	QL1.1 Improve Community Quality of Life	Assessed	6	1	2	0	0	0	0	2	26	26
		QL1.2 Enhance Public Health & Safety	Assessed	5	1	0	0	0	0	0	0	20	20
		QL1.3 Improve Construction Safety	Assessed	3	2	0	0	0	0	--	0	14	14
		QL1.4 Minimize Noise & Vibration	Assessed	4	1	1	0	0	0	0	1	12	12
		QL1.5 Minimize Light Pollution	Not Applicable	0	0	0	0	0	0	0	0	0	12
		QL1.6 Minimize Construction Impacts	Assessed	5	1	0	0	4	0	--	4	8	8
	Mobility	QL2.1 Improve Community Mobility Access	Not Applicable	0	0	0	0	0	0	0	0	0	14
		QL2.2 Encourage Sustainable Transportation	Not Applicable	0	0	--	0	0	0	0	0	0	16
		QL2.3 Improve Access & Wayfinding	Assessed	4	0	0	0	0	14	--	14	14	14
	Community	QL3.1 Advance Equity & Social Justice	Not Applicable	0	0	0	0	0	0	0	0	0	18
		QL3.2 Preserve Historic & Cultural Resources	Not Applicable	0	0	--	0	0	0	0	0	0	18
		QL3.3 Enhance Views & Local Character	Not Applicable	0	0	0	0	0	0	0	0	0	14
		QL3.4 Enhance Public Space & Amenities	Not Applicable	0	0	0	0	0	0	0	0	0	14

Figure XI.A.I: Quality of Life Sustainability

B. Leadership

For an interdisciplinary project, communication and effective leadership played key roles in the success and progress of the entire group. As can be visualized in the figure below, ZARP believed that Collaboration and Teamwork have been well accounted for. The meeting schedule, the willingness to communicate between the subgroups, and the ability to work efficiently together all led to this conclusion. The Provide for Stakeholder Involvement was also a main category that ZARP focused on. Dr. Ley, the primary stakeholder during the Spring 2020 semester, had numerous things he wanted to discuss to get his point across. ZARP believed they provided what he asked for as well as helped with anything that could be beneficial for the overall project.

Another primary focus of this team was Pursuing Byproduct Synergies. Being at the Bert Cooper Laboratory, the majority of forms created were able to be made with scrap wood. Also, scrap metal was utilized in the mechanical design as well. Lastly, the aggregates already at Cooper were able to be sieved and utilized.

			Credit Assessment Status	Evaluation Questions Assessed		Assessment Status						Assessed Maximum Points Available	Total Maximum Points
				Yes	No	Improved	Enhanced	Superior	Conserving	Restorative	Points		
Leadership	Collaboration	LD1.1 Provide Effective Leadership & Commitment	Assessed	3	1	0	0	12	0	--	12	18	18
		LD1.2 Foster Collaboration & Teamwork	Assessed	4	0	0	0	0	18	--	18	18	18
		LD1.3 Provide for Stakeholder Involvement	Assessed	6	0	0	0	0	0	18	18	18	18
		LD1.4 Pursue Byproduct Synergies	Assessed	5	0	0	0	0	0	18	18	18	18
	Planning	LD2.1 Establish a Sustainability Management Plan	Assessed	4	1	4	0	0	0	--	4	18	18
		LD2.2 Plan for Sustainable Communities	Assessed	4	1	0	0	0	12	0	12	16	16
		LD2.3 Plan for Long-Term Monitoring & Maintenance	Not Applicable	0	0	0	0	0	0	--	0	0	12
		LD2.4 Plan for End-of-Life	Not Applicable	0	0	0	0	0	0	--	0	0	14
	Economy	LD3.1 Stimulate Economic Prosperity & Development	Assessed	4	1	0	0	0	0	--	0	20	20
		LD3.2 Develop Local Skills & Capabilities	Not Applicable	0	0	0	0	0	0	0	0	0	16
		LD3.3 Conduct a Life-Cycle Economic Evaluation	Assessed	5	0	0	0	0	0	14	14	14	14

Figure XI.B.I: Leadership Sustainability

C. Resource Allocation

The primary focus from the Resource Allocation category that ZARP addressed was using recycled materials. The aggregate ingredients in the mixture could be found anywhere in the world because sand and rock are quite common. These ingredients would be able to be sourced anywhere which ZARP felt was important. The special components of the mixture may be outsourced, but not every design is perfect. As for recycled materials, the mixture design replaced 20% of the OPC with Fly Ash. Fly Ash is a byproduct from coal burning power plants. ZARP believes this was a major use of recycled materials. In the future, the mixture could possibly be optimized by utilizing recycled crushed brick or other recyclable components.

			Credit Assessment Status	Evaluation Questions Assessed		Assessment Status						Assessed Maximum Points Available	Total Maximum Points
				Yes	No	Improved	Enhanced	Superior	Conserving	Restorative	Points		
Resource Allocation	Materials	RA1.1 Support Sustainable Procurement Practices	Assessed	1	1	0	0	0	0	--	0	12	12
		RA1.2 Use Recycled Materials	Assessed	1	0	4	0	0	0	--	4	16	16
		RA1.3 Reduce Operational Waste	Assessed	0	2	0	0	0	0	--	0	14	14
		RA1.4 Reduce Construction Waste	Assessed	1	1	0	0	0	0	--	0	16	16
		RA1.5 Balance Earthwork On Site	Assessed	1	0	2	0	0	0	--	2	8	8
	Energy	RA2.1 Reduce Operational Energy Consumption	Assessed	2	0	6	0	0	0	--	6	26	26
		RA2.2 Reduce Construction Energy Consumption	Assessed	2	0	0	4	0	0	--	4	12	12
		RA2.3 Use Renewable Energy	Not Applicable	0	0	0	0	0	0	0	0	0	24
		RA2.4 Commission & Monitor Energy Systems	Assessed	0	3	0	0	0	0	--	0	14	14
	Water	RA3.1 Preserve Water Resources	Not Applicable	0	0	0	0	0	0	0	0	0	12
		RA3.2 Reduce Operational Water Consumption	Assessed	4	0	4	0	0	0	0	4	22	22
		RA3.3 Reduce Construction Water Consumption	Assessed	2	0	1	0	0	0	--	1	8	8
		RA3.4 Monitor Water Systems	Not Applicable	0	0	0	0	0	0	--	0	0	12

Figure XI.C.I: Resource Allocation Sustainability

D. Natural World

ZARP analyzed two topics within the Natural World category that somewhat applied to the 3D concrete printing group's project. The rest were marked as non-applicable. ZARP focused on the topics of Preserve Undeveloped Land and Protect Soil Health. With this in mind, the group believed minimizing the cement content in the mix was better for the environment which includes the soil. Also, the homes would only be built where allowed, meaning that land meant to be undeveloped would remain so.

			Credit Assessment Status	Evaluation Questions Assessed		Assessment Status						Assessed Maximum Points Available	Total Maximum Points
				Yes	No	Improved	Enhanced	Superior	Conserving	Restorative	Points		
Natural World	Siting	NW1.1 Preserve Sites of High Ecological Value	Not Applicable	0	0	0	0	0	0	0	0	0	22
		NW1.2 Provide Wetland & Surface Water Buffers	Not Applicable	0	0	0	0	0	0	0	0	0	20
		NW1.3 Preserve Prime Farmland	Not Applicable	0	0	--	0	0	0	0	0	0	16
		NW1.4 Preserve Undeveloped Land	Assessed	1	1	3	0	0	0	0	3	24	24
	Conservation	NW2.1 Reclaim Brownfields	Not Applicable	0	0	0	0	0	0	0	0	0	22
		NW2.2 Manage Stormwater	Not Applicable	0	0	0	0	0	0	0	0	0	24
		NW2.3 Reduce Pesticide & Fertilizer Impacts	Not Applicable	0	0	0	0	0	0	0	0	0	12
		NW2.4 Protect Surface & Groundwater Quality	Not Applicable	0	0	0	0	0	0	0	0	0	20
	Ecology	NW3.1 Enhance Functional Habitats	Not Applicable	0	0	0	0	0	0	0	0	0	18
		NW3.2 Enhance Wetland & Surface Water Functions	Not Applicable	0	0	0	0	0	0	0	0	0	20
		NW3.3 Maintain Floodplain Functions	Not Applicable	0	0	0	0	0	0	0	0	0	14
		NW3.4 Control Invasive Species	Not Applicable	0	0	0	0	0	0	0	0	0	12
		NW3.5 Protect Soil Health	Assessed	4	0	--	0	4	0	0	4	8	8

Figure XI.D.I: Natural World Sustainability

E. Climate and Resilience

About half the categories within this section were not applicable to this project. However, ZARP believed that there was a need to analyze the emissions produced from this project. The "Reduced Net Embodied Carbon" was given great evaluation as ZARP felt utilizing a full on concrete mixture unlike the mortar mixture used in other 3D printing greatly reduced the CO2 emissions, hence reducing the carbon emitted. It reduced the CO2 by greatly reducing the amount of OPC in the mixture by utilizing coarse aggregates. Also, this coincided somewhat with "Reduce Air Pollutant Emissions". Also, for this category, using less machinery to build the home on site would most likely lead to lessened emissions overall.

			Credit Assessment Status	Evaluation Questions Assessed		Assessment Status						Assessed Maximum Points Available	Total Maximum Points
				Yes	No	Improved	Enhanced	Superior	Conserving	Restorative	Points		
Climate and Resilience	Emissions	CR1.1 Reduce Net Embodied Carbon	Assessed	3	0	--	0	0	0	--	0	20	20
		CR1.2 Reduce Greenhouse Gas Emissions	Assessed	2	0	8	0	0	0	0	8	26	26
		CR1.3 Reduce Air Pollutant Emissions	Not Applicable	0	0	0	0	0	0	0	0	0	18
	Resilience	CR2.1 Avoid Unsuitable Development	Not Applicable	0	0	0	0	0	0	0	0	0	16
		CR2.2 Assess Climate Change Vulnerability	Not Applicable	0	0	0	0	0	0	--	0	0	20
		CR2.3 Evaluate Risk and Resilience	Assessed	6	0	11	0	0	0	--	11	26	26
		CR2.4 Establish Resilience Goals and Strategies	Assessed	4	0	--	0	0	20	--	20	20	20
		CR2.5 Maximize Resilience	Assessed	4	1	0	0	20	0	--	20	26	26
		CR2.6 Improve Infrastructure Integration	Not Applicable	0	0	0	0	0	0	0	0	0	18

Figure XI.E.I: Climate and Resilience Sustainability

XII. Project Cost Estimate

The 3-D concrete printing project had two aspects to it with respect to cost estimates. First, the team needed to work within a budget in order to create a cost-effective system. The engineers on this project were able to stay well within budget. Second, the team needed to provide an estimate for how much the actual system would cost to run on a site as well as possible man-hours it would take. These two analyses can be seen in sections A and B respectively below.

A. Material Cost Analysis

Given by the client, the total materials budget for this project was approximately $8,000. However, this amount was subject to change due to the extensive research of the overall project. As shown in the tables that follow, ZARP stayed well within budget with plenty of room for contingencies. The material analysis included materials that had been bought along with those that were required for the project. The materials and their necessary information are shown in Table XI.A.I on the following page. Also, the concrete cost for the civil side of the project is shown in Table XI.A.II.

As will be seen in the two tables, the total cost was approximately $7,300.00. This is $700.00 under the $8,000 budget. Also, this incorporated just under $2,000.00 worth of contingencies as deemed appropriate by the mechanical engineers. With this known, ZARP felt confident in delivering a cost-effective method of creating a 3-D printing system.

Table XII.A.I: Material Cost Analysis

Material Cost Sheet			
Quantity	*Item*	*Price*	*Actual Cost*
	Mechanical Parts		
1	Hydraulic Power Pack	$ 1,579.99	$ 1,579.99
1	Hydraulic Motor	$ 469.58	$ 469.58
2	Hydraulic Hose	$ 39.28	$ 78.56
1	Hydraulic Miscellaneous	$ 250.00	$ 250.00
1	8 Foot Auger	$ 476.00	$ 476.00
1	Auger Blade Extensions	$ 83.95	$ 83.95
2	Bearings	$ 45.00	$ 90.00
1	Miscellaneous Fasteners	$ 75.00	$ 75.00
1	4” Tubing – 12 Foot	$ 125.00	$ 125.00
1	Pipe Reducer	$ 62.00	$ 62.00
1	Pipe Elbow	$ 150.00	$ 150.00
1	Steel Tubing 9” x ¼” x 24”	$ 336.00	$ 336.00
1	Steel Tubing 5” x 3” x ¼” – 6 Foot	$ 112.86	$ 112.86
3	Steel Tubing 6” x 0.125” – 8 Foot	$ 146.44	$ 439.32
1	Square Tubing 1” x 14GA x 24 Feet	$ 31.92	$ 31.92
2	Vibration Generator	$ 236.90	$ 473.80
	Electrical Parts		
1	Raspberry Pi	$ 30.00	$ 30.00
1	SD Card	$ 10.00	$ 10.00
1	18 Gauge Wire – 25 ft	$ 20.00	$ 20.00
1	USB CAN Bus Adapter	$ 65.69	$ 65.69
2	12V to 5V Converter	$ 11.59	$ 23.18
1	10A Fuse (5 pack)	$ 12.99	$ 12.99
1	Monitor	$ 70.00	$ 70.00
1	Kill Button	$ 43.44	$ 43.44
6	Buttons	$ 2.00	$ 12.00
2	Arduino	$ 10.99	$ 21.98
1	Screw Terminals	$ 6.98	$ 6.98
1	Digital Compass	$ 15.00	$ 15.00
1	Ultrasonic Sensor	$ 16.00	$ 16.00
3	LiDAR	N/A	N/A
1	Shrink Wraps	$ 12.99	$ 12.99
1	Camera	$ 20.00	$ 20.00
	Contingencies	-	$ 1,880.00
	Summation (Overall TOTAL)	-	$ 7, 093.35

Table XII.A.II: Concrete Cost Analysis

Concrete Mixture Total Cost			
Material	**Mixture Design Dosage (lb/yd^3)**	**Unit Cost**	**Cost/yd^3**
Coarse Aggregate	1232.40	$ 0.010 / lb	$ 12.42
3/8" Aggregate	426.30	$ 0.010 / lb	$ 4.32
Fine Aggregate	1387.30	$ 0.005 / lb	$ 7.02
OPC	526.40	$ 0.052 / lb	$ 27.27
Fly Ash	131.60	$ 0.023 / lb	$ 2.97
Citric Acid	1.66	$ 3.700 / lb	$ 6.21
Nano-Clays	1.43	$ 4.500 / lb	$ 6.48
DARACEM 55	1.28	$ 6.000 / lb	$ 7.56
Total Cost/yd^3			$ 74.25
Mixes for Semester Cost (0.11yd^3/week for 11 weeks)			$ 90.66
Cost of 2 Trial 5' x 3' x 8" Walls (0.37yd^3 each)			$ 54.95
Cost of Final 5' x 3' x 8" Wall (0.37yd^3)			$ 27.47
Contingency (0.37yd^3)			$ 27.47
Total Concrete Cost for Semester			**$ 200.56**

B. Operational On-Site Cost Analysis

This semester, ZARP was unable to produce the wall with an operating mechanical system due to mechanical struggles along with COVID-19 putting a halt to all progress over a month out from the project being due. However, the civil engineers still believe in the estimation shown below focused on utilizing the 3-D concrete printing system. The estimation includes concrete placement and finishing touches along with machinery and labor hours on site.

The information that follows was based on estimates in Oklahoma according to the RSMeans database as well as researched quotes for average cost of machinery.

- <u>Labor Cost</u>
  - 1 – Skilled Worker ($54.85 / hour / person)
    - Contractor in charge
  - 4 – Helpers ($39.95 / hour / person)
    - 1 Safety person
    - 2 Extra people helping with concrete mixing / quality testing
    - 1 Person in skid steer
- <u>Machinery Cost</u>
  - ZARP's Mechanical System ($450.00 / week)
  - John Deere Skid Steer 320E ($600.00 / week)
    - Capable of attaching ZARP's mechanical system
  - Small Concrete Mixer ($300.00 / week)

        - 6 cubic feet gas mixer
- Concrete Cost (From Table XII.A.II)
    - $74.25 / cubic yard
- Estimated Extrusion Rate
    - 10 cubic feet / hour *or* 0.37 cubic yards / hour

Based on the estimated extrusion rate and cost above, the estimated cost of placing concrete on site would be **$744.93 / cubic yard**.

Once the mechanical system became fully operational, the actual rate of extrusion could be determined. With this information, a full cost analysis could be determined based on placement in cubic yard of concrete. There will need to be major readjustments most likely as ZARP has never seen the mechanical system operational. This rate can change based on capability of machinery as well as loading rate of concrete to the hoppers system.

XIII. Project Summary and Conclusions

ZARP took on multiple aspects of the 3D Printing Project this semester. The mechanicals figured out a few more aspects of their design that was flawed from last semester. The electricals were able to understand how to code a skid steer. The civil engineers were able to pursue numerous aspects of the concrete side of the project that had not been looked at yet. These include vibration methods, pulp curing, and dual extrusion which were able to be somewhat analyzed with coring and testing.

All that was done this semester was in hopes of reaching the end goal of utilizing a skid steer to autonomously print a 3' x 5' x 8" straight wall. The mechanical engineers somewhat figured out what was wrong with their system, however, they did not act fast enough to get a working system put together before spring break. Also, the electrical engineers, while they figured out much of what they needed, did not have time to see if their coding worked.

This section will identify what was done this semester primarily from the civil engineers' standpoint as well as the conclusions drawn from each major aspect they investigated.

A. Spring 2020 Coring and Testing

The cores and respective density and compressive strength testing performed this semester gave insight into numerous aspects of the civil side of this project. There were cores taken on a control wall, the Fall 2019 wall, and a dual extruded wall from this semester. Each core was extracted with the vertical structure laying on its backside correlating to taking cores on or between layers. While there was not enough data to draw sufficient claims at this point due to the COVID-19 pandemic, the Next Steps section sheds light on future testing for next semester's group.

B. Vibration Method

From this semester, the vibration technique found most effective was applying vibration perpendicular to the surface. This allowed wave propagation to act in the proper manner. Shown throughout this document, numerous trials were performed for various techniques. The perpendicular technique offered the most pleasing aesthetics and finishable surface which is what ZARP was initially looking for.

Consolidation was also able to minimize voids and protect the rebar from outside corrosive causing chemicals. There could be various tests ran in the future to see if this vibration method provides higher qualities than the control wall. Shown in the Next Steps is how to further the investigation into proper vibration technique.

C. Pulp Curing

Curing, as has been proven by many professionals focused on concrete, leads to minimizing pore spacing and increased concrete strength. Proper curing could improve the concrete properties both short term and long term. However, curing could also increase cost up to 3% and increase time of construction.

For this project, it was evident that if curing was to be applied, pulp cure was the method of choice. This was the only method that cooperated with vertical structures other than curing compounds. ZARP has ran no tests on curing compounds. Pulp Curing is a combination of shredded newspaper, water, and possibly tackifier if deemed necessary. This semester, ZARP created a wall and applied pulp cure, a shredded newspaper and water blend, to the wall in about ½" thickness. The wall was then covered in a tarp to help prevent additional evaporation. However, this was done the day prior to Oklahoma State University restricting access to the laboratories due to the COVID-19 pandemic. Therefore, while ZARP cannot prove this will help aid the strength and overall wall properties, all data to be collected to help prove this theory must be for future groups. The method of testing will be shown in the Next Steps section.

D. Dual Extrusion

From ZARP's attempt at utilizing dual extrusion this semester with a procedure shown in Appendix C, it seemed that dual extrusion was the method for the future groups to pursue. This semester, ZARP wanted to further investigate it; however, the mechanicals and electricals did not believe they would be able to get it to work with their knowledge of the mechanical system. However, the civil engineers believed there could be a way to keep their system and still be able to add on the necessary dual extrusion components.

There are multiple reasons ZARP believed dual extrusion was promising. First, the manual dual extruded print ZARP performed was extremely effective in pushing the concrete around the rebar and allowing it to be more cohesive. Second, the forces of pushing concrete from both sides eliminated the need for a backform. Third, these forces also could potentially allow the layers to be further pushed together and overall, more cohesion leading to strength gain. Fourth, printing from each side correlated to a 4" wall thickness required from each pipe instead of requiring concrete to travel 8" before moving the skid steer. This could lead to a quicker, more controlled print, and overall, more cost effective in decreasing time of machinery and personnel on site.

There was a debate amongst the engineering disciplines on whether dual extrusion should even be pursued. The civil engineers strongly believed in this method. When looking at the selected approach, there was the possibility of leaving the system as is. The only difference would be having a 4" pvc or metal piping network go up and over the consolidation formwork. This would allow concrete to be printed from that side as well. Obviously, there were complications with this as pumping pressures and gravity came into play. However, future civil engineering groups should pursue and find multiple ways to allow this method to work in order to convince the mechanical and electrical engineers.

XIV. Next Steps for Project

The Spring 2020 semester had limited progression due to unforeseen circumstances. However, ZARP was allotted the rest of the time after spring break to fully document the information gathered this semester. Therefore, the following sections are what the civil engineers believe to be proper ways to further progression towards the desired end-goals and how to expedite the civil side of the project with a procedural layout of how to continue.

A. Coring and Testing

Each section below can be tested with coring the walls. Coring is a vital method in understanding the in-place strength of the wall compared to the actual design values. Whether testing single extrusion, dual extrusion, vibration techniques, or curing effectiveness, the process to test cores is as shown in the Data Gathered and Analysis section. Coring and its' respective testing has been mentioned abundantly. Most importantly, coring this semester was done horizontal to the wall. This can be visualized in Appendix C. However, there is additional testing to be done as shown in the sections below.

What the sections below do not necessarily mention is how to possibly alter different parts of the mixture design to cooperate with vibration or dual extrusion. If the vibration method absolutely does not work, there could be a need for more citric acid, nano-clays, or water reducer depending on the observation. This would cause the need for multiple mixes and Oopsie tests to further investigate cooperativeness between mixture design and vibration or placement technique. The

Oopsie test procedure can be seen in Appendix C. ZARP does not believe they have sufficient evidence to further provide advice on altering mixture design.

B. Vibration Method

The method of vibration has already been decided on through preliminary testing shown in the Alternatives Analysis section. However, because a stinger vibrator is not the vibrator to be used, testing is still necessary. The first step for the next group is to acquire two of the vibrator packs as shown on the material list in the mechanical items. Once these are able to be operated, the next step would be to begin testing on Oopsie tests.

Oopsie tests are generally 4" wide, however, because the actual wall will be 8" wide, it is necessary to do a dual Oopsie test, that is create two stacks right next to eachother. Once there is a plate with the vibrator pack attached, similar to what will be used in the actual system, on either side of the Oopsie, testing can begin. The tests should be based on aesthetics as follows.

1. Create two to three layers of the Oopsie test
    a. Set the frequency to a determined mildness that seems appropriate (ZARP cannot give insight on this as the frequency is unknown that the vibrator pack can operate)
    b. Allow it to run for approximately 15 seconds
    c. Observe each side and see if the method was effective / still allowed for a sharp stiff edge
2. Repeat this process numerous times to dial in a proper frequency and longevity of vibration that provides adequate results along with stack ability.

This process, like much of the civil side of the project, took time along with a keen eye for detail. Unlike some engineering topics, this topic required the engineer to observe and make judgement calls.

C. Pulp Curing

A wall was created with pulp cure applied to it in Spring 2020. However, the pandemic halted the progress of testing it.

For future groups, the first step would be to core this wall and compare its strength value to that of the cores taken this semester. If it is higher, which it should be, then this is a viable method to pursue.

After initial testing, the next step in understanding pulp cure would be to test different times and thicknesses required. After all, the end-goal of the entire project is to create an industry approved procedure. Several smaller walls, still 8” in thickness, could be created and tested in the following manner.

1. Create 4 smaller walls (3’ length x 1’ height x 8” thickness)
    a. Wall #1 – control
        i. Take 3 cores 7 days after set and follow method stated in the coring section of Data Gathered and Analyzed
        ii. Test for Compressive Strength after grinding ends
    b. Wall #2 – ½” thick pulp cure applied for 1 day
        i. Remove pulp cure after 24 hours
        ii. Take 3 cores after 7 days
        iii. Test for Compressive Strength after grinding ends
    c. Wall #3 – ½” thick pulp cure applied for 3 days
        i. Remove pulp cure after 72 hours
        ii. Take 3 cores after 7 days
        iii. Test for Compressive Strength after grinding ends
    d. Wall #4 – ½” thick pulp cure applied for 7 days
        i. Take 3 cores after removal of pulp cure
        ii. Test for Compressive Strength after grinding ends
2. Compare the data for all 7-day values for each wall
3. For the mixes used:
    a. Take slump and unit weight
    b. Create 6 control cylinders per mix
    c. Compare the design strength values to in-place values
        i. It is important to know how in-place concrete correlates to the compressive strength of the cylinders made. We would like to see consistent strengths > 4000 psi as we were not seeing values from our previously tested cores anywhere similar to that of the cylinders made with the wall.
4. Recreate this process to take cores at 28 days as well to get values resembling the long-term concrete properties.

This process could also be replicated for trying different thickness of pulp cure applied. It is easy but will require time mixing and ensuring the mix is the same for each wall to properly test the differences. It is vital to grind the ends of the cores to prevent eccentricities.

D. Dual Extrusion

For the future groups, dual extrusion can be investigated the same way ZARP found the properties of the Fall 2019 wall which was through coring. Initially, the future group can take cores out of the dual extruded wall ZARP created to test for strength. However, the best option is to produce a wall utilizing the same method, finish the wall properly, unlike ZARP, and then take cores as follows.

1. Create a 5’ length x 3’ height x 8” thick wall (Finish it but no consolidation)
    a. Take 3 cores in the bottom layer only after 7 days
        i. Test for Compressive Strength after grinding ends
    b. Take 3 cores between the bottom and second layer after 7 days
        i. Test for Compressive Strength after grinding ends
    c. Take 3 cores in the third layer only after 7 days
        i. Test for Compressive Strength after grinding ends
2. Compare the data for all 7-day values for each core
    a. Gives better idea if wall location matters
3. For the mix used to create the wall:
    a. Take slump and unit weight
    b. Create 6 control cylinders per mix
    c. Compare the design strength values (control cylinders) to in-place values
        i. It is important to know how in-place concrete correlates to the compressive strength of the cylinders made. We would like to see consistent strengths > 4000 psi as we were not seeing values from our previously tested cores anywhere similar to that of the cylinders made with the wall.
4. Recreate this process to take cores at 28 days as well to get values resembling the long-term concrete properties.

This process can be replicated if applying vibration to test effects of that as well. Once the mechanical system is operational, it would be necessary to repeat this process on the wall created with that system in order to see if any changes occurred.

For dual extrusion, the data acquired from manually printing the wall as ZARP did may be necessary to further convince the mechanical engineers the need for this method. Also, ways of converting the system to accommodate dual extrusion need to be thought of in depth. ZARP is proposing simply having a pipe network attached to the consolidation framework to move concrete to that side of the traveling form. However, the counterweight necessary to achieve this is unknown as well as if the auger system would even allow this method to be possible.

XV. Appendices

Appendix A – References Cited (All Groups Included)

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Appendix B – Summary of Discussions with Client

Discussion #1: (01/16/2020)

In the first quick meeting with the team, everyone got to know each other and discuss the end goal for the project. A tour of the lab was performed as well as a meeting schedule was enacted. Meetings were to take place every Wednesday at 4:30 pm for the remainder of the semester. Jim Beckstrom would be aiding the mechanicals in their design process, Dr. Ley would be offering some advice to the civils, and Dr. Ekneligoda will be offering help to the electricals.

Discussion #2: (01/22/2020)

Throughout the first real meeting, or second meeting total, with Dr. Tyler Ley, Professor Beckstrom, and the students involved, there were numerous ideas passed around. The Civil Engineers planned on getting right to work with taking cores of the old wall and performing quality control tests prior to week three in order to start on a new, improved mixture design. The Electrical Engineers had already planned on how to start getting the skid steer to work autonomously and were ready to purchase materials. The Mechanical Engineers were slightly confused on an appropriate path to take, but the client helped them out. The client had stated that sustainability was of the utmost importance for this project and was fond of the ideas the civil and electrical engineers had. The client had also made it clear to the mechanical engineers that money is not of importance and neither was the previous year's design. They have full range to develop a working pump that they feel is economical, sustainable, and efficient.

Discussion #3: (01/29/2020)

The third meeting with the doctors and professors went quite well. The civil students explained their testing on the cores from the previous semester for density and strength. Dr. Ley was excited for the civils to produce results so quickly, but also allowed the students to realize they rushed the test which could have given them skewed results. With this known, the civil students planned on executing more cores and testing to occur over the next couple weeks. The civils also planned on utilizing dual extrusion to see if it worked. The mechanicals had not done much over the last week but had planned on tinkering with the old hopper system to see what was still useable for this project. The electricals were able to look at the skid steer and prepare a list of materials they needed to buy to begin analyzing the coding system.

Discussion #4: (02/12/2020)

In the fourth meeting, the civils presented their findings on the dual extrusion method as well as mentioned the cores were still in the process of being tested. The mechanicals had utilized the never-set concrete mixture civils provided them, but their system was not able to function properly. The electricals were waiting on materials to arrive for their coding but were making progress in applying models for their end-goal. Professor Beckstrom was not supportive of the dual extrusion because he felt the civils were not being a part of the team. The civils, however, had Dr. Ley's full support in this endeavor. After speaking with Professor Beckstrom, the civils decided to do the single extrusion as they understood the mechanicals were not able to produce a more complicated system.

Discussion #5: (02/19/2020)

In the fifth meeting of this semester, the mechanicals brought up that they know they needed a stronger motor for the auger and would be researching new ways to improve it. The electricals began decoding and it looked promising! The civils were able to produce compressive strengths and density tests for the three cores taken and they show promising results in terms of voids. However, the strength is low which may be skewed by how the cores were taken. Dr. Ley wants more cores to compare the layers. The civils were also able to start trials of consolidation methods. Overall, the advisors were generally okay with the progress but concerned on the civils and mechanicals. Beckstrom wanted to know why the mechanicals are still stuck and haven't found a way to progress! Dr. Ley gave the same lecture to the civils.

Discussion #6: (02/26/2020)

In the last meeting of February, the group went over how the final design review would go. Dr. Ley and Beckstrom were pleased with the findings of the civil group on vibration perpendicular to the plates in order to consolidate the layers. The mechanicals performed a torque test and found out they needed a motor to produce about 130 lb-ft of torque. The one currently only produced 58 lb-ft of torque. The electricals said the "sniffing" of data will take a lot of time and require new software, but they were confident it will be able to get done. The students were able to ask Beckstrom anything necessary and pertaining to the final design review presentation or the report as well.

Discussion #7: (03/04/2020)

For the first meeting in March, the team reviewed how the final design review presentation went and what could be improved. The mechanicals offered some advice on the consolidation system the civils are focusing on. However, their advice was something that would not work. They wanted to try and test the compressive strength of FRESH concrete by using a scale on each side and applying pressure to the wall. This idea was talked over and declined by the civils and professors. The mechanicals planned on utilizing a power pack instead of the hydraulic power from the skid steer. The civils plan on continuing trials of the selected consolidation method as well as determining properties of last year's wall. The electricals planned on continuing decoding of the skid steer.

Discussion #8: (03/11/2020)

Right before spring break, the team had their eighth meeting of the semester. The mechanicals and electricals both had shown decent progress even though the mechanicals had yet to actually put forth a working system. They had been focusing on independent research. The civils had made a lot of progress to this point on the consolidation method; however, the clients were unimpressed with their progress. Dr. Ley had a separate meeting with them to instruct them on having a proper method of moving forward.

Discussion #9: (03/25/2020)

This meeting was via ZOOM. The discussion immediately after spring break was an extremely informative meeting. Each of the students working on the project stated their contributions thus far to the project and the clients spoke on what they agreed or disagreed with. Also, the clients spoke on how to try to rescope the project to make it more realistic and attainable for this semester due to the COVID-19. The civils had already pitched their idea to Dr. Ley who offered his feedback and was pleased with the plan of moving forward. They made plans to meet the next day (Thursday).

Discussion #10: (03/26/2020)

This meeting was via PHONE. Dr. Ley and the civil students met the day after the entire group met. They went over the specifics of the proposal from the students and Dr. Ley offered his immediate feedback. The civils had questions on how to move forward and he gave great insight. They planned to meet one week from today with more information in both PowerPoint and document form on how to fully document dual extrusion, pulp cure, vibration, and coring of the walls.

Appendix C – Procedural Setups

Coring Information

<u>Materials List:</u>

- Coring Machine
- Tension Rod
- Generator or capable power source
- Electric Cord
- Water Hose
- Steady supply of water

<u>Setup:</u>

1. Gather all necessary materials
2. Position coring machine over the designated area decided to extract core from
3. Ensure the coring machine is LEVEL
4. Attach tension rod between top of machine and ceiling (secure it well)
5. Attach water hose to coring machine from steady water supply
6. Make sure all power switches are off and then plug machine into power source
7. If using generator, turn generator on
8. Make sure all appropriate gauges are working
9. Allow water to start being applied to the machine
10. Once water is running through it visibly, the process can begin

<u>Procedure:</u>

1. Once water is running through system, turn on coring machine
2. The metal piece on the guide rail needs to be loosened
3. Always keep hand on 4 piece turn knob, once the metal piece has been loosened, slowly turn the knob towards you (counterclockwise if looking at machine from side)
4. Make sure, when reaching the concrete to core, that pressure is applied
5. Once the pressure begins, keep the gauge between 10 – 20 psi to ensure an adequate exterior of the core
6. The coring machine will generally take about 10 minutes to extract one core
    a. The person utilizing the machine should be able to feel when the core has been extracted
    b. If the person does not feel it, the sound the machine makes also changes due to less energy having to be applied. The rotations increase rapidly
7. Once core is extracted, being moving the turn knob clockwise and shut off the machine
8. After machine is shut off, tighten the metal piece on guide rail to keep in place
9. Repeat this process as needed, making sure machine is level each time

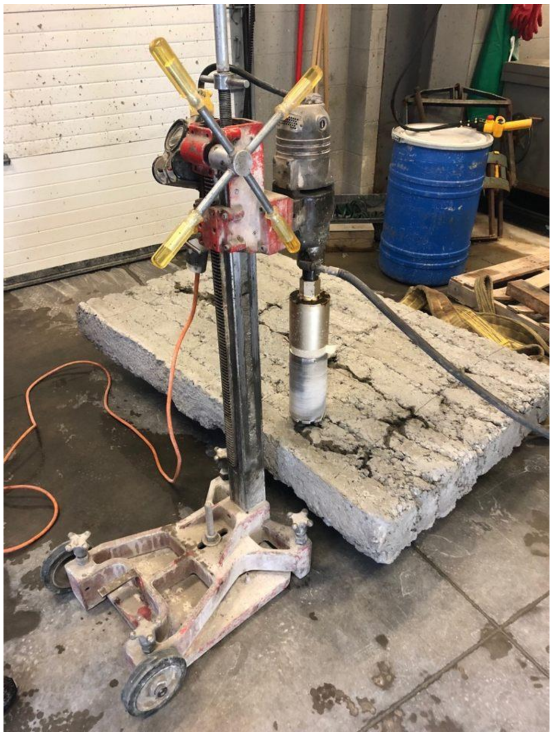


Figure XV.C.I: Coring Process Pictures

The figures above show the machine in an operationally ready state. The tension rod up top is tight, water is connected, and power is connected. The figure on the right shows the machine being operated as on is controlling the machine, and the other person is ensuring the pressure is evenly applied.

Oopsie Test Information

Materials List:

- Cylinder with end removed
- Consolidation Rod
- “Plunger” – the circular piece attached with a rod as will be shown below
- Base plate with rebar (optional) – helps to see formation around rebar
- Concrete

Setup:

1. Gather all necessary materials
2. Have two surfaces, one where consolidation is occurring and the other where the oopsie test is performed
3. Create mixture design for concrete based on Tarantula Curve

Procedure:

1. Once mixture design is ready, perform the moisture correction, batch materials, and mix the concrete

2. After concrete is mixed properly, begin performing Oopsie Tests
3. Start by placing a plate under the cylinder with no ends, then begin adding concrete and consolidating it with a rod in two lifts (leave room in cylinder to place the "Plunger")
4. Once consolidated, grab cylinder with no ends and place "Plunger" to one end
5. Careful not to squeeze the cylinder, let the hand with the "Plunger" slowly extrude the concrete
    a. Using observations, measure the stiffness and flow ability of the concrete
    b. If not to satisfaction, adjust mixture
6. Continue this process by placing layer after layer to see how stiff the mix is, if it can continuously hold its edge, and if the bottom layers start to compress it is evident there needs more time between layers or there needs more stiffness in the mixture
7. While an Oopsie Test can be done without the base plate and rebar, the base plate with rebar allow observations on if the mixture will form around the rebar
    a. ZARP feels this is a vital test as cohesion to rebar is what makes a reinforced structure properly withstand forces that cause tension on the structure.

Materials

Oopsie Test

Figure XV.C.II: Oopsie Test Pictures

Dual Extrusion Information

<u>Materials List:</u>

- Forklift
- 2 - 4" Diameter PVC pipes with angular cuts
- Multiple Ratchet Straps
- 2 - "Plungers" (Attached to Long 1" PVC Pipes)
- 2 - Rebar (#4 preferably) cut to height greater than desired printing height
- Bottom Formwork to print onto (Forklift accessible)

Setup:

1. Gather all necessary materials
2. Push the forks from the forklift close together (shown below)
3. Place 4” PVC pipe similar as shown below, try to ensure they are approximately 8” apart
4. Secure 4” PVC pipes to forklift with ratchet straps
5. To help with angle of the PVC – may have to extend forks by adding 2x4’s
6. Place #4 Rebar in Bottom Formwork and put the formwork in location that is accessible for print

Procedure:

1. Once the setup is ready and the concrete is mixed, bring the concrete in a wheelbarrow or two out to where the printing will occur
2. *Will need 5 People to Properly Operate*
    - 1 Person Operating Skid Steer
    - 2 People Guiding 4” PVC / Calling out rate of extrusion
    - 2 People Extruding the concrete from the 4” PVC with “Plungers”
3. Place a trowel on the end of each 4” PVC pipe, and begin filling both up
4. Once they are near being full, each person is able to start pushing the concrete
5. When the people holding the trowels feel a lot of pressure, remove the trowels and allow the concrete to extrude onto the formwork
6. Person driving the skid steer can begin moving backwards while the two people extruding the concrete remain equal pressure
7. Be careful to go slow enough to allow the concrete to mesh together and form around rebar
8. Replace this process for each layer

Figure XV.C.III: Some Dual Extrusion Components

Figure XV.C.IV: More Dual Extrusion Components

Appendix D – Supporting Computer Printouts and Hand Calculations

Mixture Design Utilizing Tarantula Curve (Performed in Excel)

To utilize the Tarantula Curve, one must have access to Excel. There is a tutorial video on how to properly use this program on Dr. Tyler Ley's YouTube page. The list below shows what is needed to use this excel sheet.

- Aggregate Properties
  - Gradation
  - Specific Gravity
- Desired Air Content
- Desired Water to Cement Ratio

After knowing these components, one can plug the sieve analysis into the excel sheet. After some maneuvering, the air content and water to cement ratio can be plugged in. Finally, it is simply plugging and chugging amounts of aggregates based on gradation and examining the Tarantula Curve. Generally, the goal is to be approximately 2% away from each border of the Tarantula Curve; however, if all the values are within it, the mixture should be sufficient.

Once the mixture design has been settled, simply collect the aggregates and perform a moisture correction to correct the design.

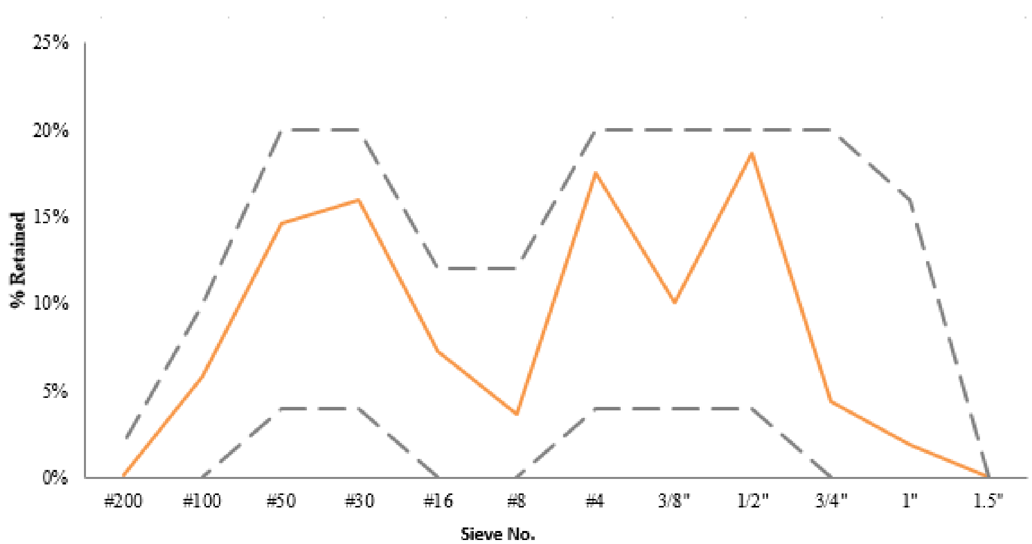


Figure XV.C.V: Tarantula Curve

Appendix E – Team Management Plan

Team Name: ZARP

Civil Engineering Team Members: (Advisor - Dr. Tyler Ley)

- Chris Filip
  - Will be focusing on the mixture design aspect of the project.
  - Personal Information:
    - (706) 945-9510
    - Christopher.filip@okstate.edu

- Rachel Schwarz
  - Will oversee documents as well as helping with the overall project.
  - Personal Information
    - (405) 312-9570
    - Rachel.schwarz@okstate.edu

- Trevor Galusha
  - Will be focusing on communications, documents, and helping with the overall project.
  - Personal Information
    - (580) 542-9059
    - Trevor.galusha@okstate.edu

- Jake Flaspohler
  - Will be involved with the overall project such as concrete mixing.
  - Personal Information
    - (580) 716-5888
    - Jake.flaspohler@okstate.edu

Non-Civil Engineer Team Members:

- Mechanical Engineering (Advisor - Professor Jim Beckstrom)
  - Taylor Bunch
  - Bailey James
  - Jesse Bowser
  - Jonah Bryant

- Electrical Engineering (Advisor - Dr. Nishantha Ekneligoda)
  - Drew Stark
  - Erick Gonzalez

Leadership Plan:
Amongst the interdisciplinary team of this project, Jonah Bryant has become the leader of the complete group. Amongst the Civil's of the group, ZARP has decided that Chris Filip is in charge of mix design, Jake Flaspohler is in charge of quality control tests, Trevor Galusha is in charge of communications, and Rachel Schwarz is in charge of documents.

Communication Plan:
Communication is done through group messaging apps and email. ZARP has set up a group with everyone in the group to discuss overall topics and have also set up separate groups for discussion pertaining only to each individual group. ZARP also sends emails for topics and meetings that include the whole group, plus the faculty advisors.

Meeting Schedule:
Civil Engineering students will meet several times throughout the week as they each work at Bert Cooper Engineering Laboratory. As of now, the CIVE's plan on meeting every Monday at 5:00 pm for as long as is deemed necessary, every Wednesday at 4:30 pm to present to the interdisciplinary group and advisors, and most Friday afternoons. Fridays and additional meetings will be scheduled via GroupMe or E-mail communication that will honor everyone's personal schedule as well.

Preliminary Team Goals:
Continue the efforts of the previous semester, reperform mixes and tests and try and improve the previous mixture.

Tasks and Milestone Plan:

- Tasks
  - 3D print a concrete wall in a sinusoidal shape (3' tall, 5' long, 8" thick, 6" magnitude)
  - Continue improving mix design to be able to pump the concrete but still maintain a sharp edge.

- Milestone Plan
  - Talk with Dr. Ley every Wednesday to give progress reports and new goals for the week to come.
  - As of now, our plan is as follows:
    - Core wall from previous semester and perform quality control tests
    - Identify the properties that can be improved and work on new mixture design
    - Create several mixes of new designs and perform numerous fresh and hardened tests to assess performance
    - Meet with rest of group a minimum of once per week to relay what concrete properties their pump needs to be able to sustain

Team Vision:
ZARP envisions being able to produce a sinusoidal concrete wall that is fully automated using a skid-steer. A working mixture design has already been achieved, however, this semester ZARP will be working towards a much more optimized mix along with utilizing a more challenging form. Upon completion of the project, ZARP hopes to develop leadership and teamwork skills as well as professional skills such as communication and planning.

Appendix F – Standard Operating Procedure

OKLAHOMA STATE UNIVERSITY
NCL STANDARD OPERATING PROCEDURE

The following SOP generally follows under:

☐	SOP is for a general lab operation/process that could apply to several chemicals
☒	SOP is for a specific protocol/experiment/procedure
☐	SOP is for a specific chemical or class of chemicals with similar hazards

Section I.

Project Title:	3D Concrete Printer		
Principal Investigator/Project Manager:	James Beckstrom	Department:	MAE
Email:	James.beckstrom@okstate.edu	Phone:	(405) 744-4957
Project Duration:	16 Weeks: (1/14/2020 – 5/1/2020)		

Location of Fabrication/Testing Include room number(s) as appropriate

CEAT North Labs	DML	UAFS	
ATRC		Richmond Hills	
Other	Bert Cooper Labs		

OSU Contact Person:	John Gage	Phone:	(405) 744-5915
Local (Field) Contact Person:		Phone:	

Group/Project Members

Name	Email	Team Leader	Team Member

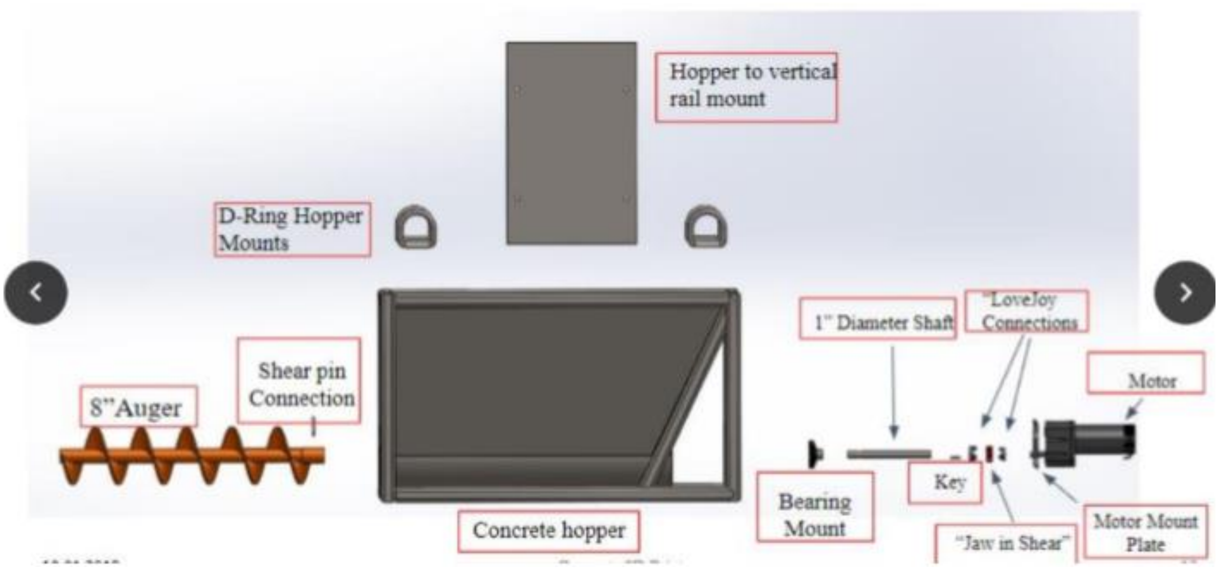
Jesse Bowser	jbowser@okstate.edu	☐	☒
Bailey James	bailey.james@okstate.edu	☒	☐
Taylor Bunch	tsbunch@okstate.edu	☐	☒
Jonah Bryant	jonahtb@okstate.edu	☐	☒
Erick Gonzalez-Lozada	gerick@okstate.edu	☐	☒
Drew Stark	drew.stark@okstate.edu	☐	☒
Jake Flaspohler	jake.flaspohler@okstate.edu	☐	☒
Chris Filip	chris.filip@okstate.edu	☐	☒
Trevor Galusha	trevor.galusha@okstate.edu	☐	☒
Rachel Schwarz	rachel.schwarz@okstate.edu	☐	☒

Section II.

The overall goal of this project is to autonomously print an 8" thick wall that is 3' tall and 5' long by integrating a skid steer with a 3D printer.

The Mechanical System

The mechanical system is made up of the skid steer, hopper system, and the dispensing system. The hopper/auger will be lined with a clear coat to prevent concrete from sticking to it. The hopper is then mounted to the fork attachment of the skid steer. The skid steer will drive forward and backwards as the hopper extrudes concrete to print each layer and the skid steer will also move the hopper up to add more layers to the wall and down to refill the hopper. The auger blade inside of the hopper will force the concrete into the dispensing system which will then extrude the concrete to form the wall. The dispensing system includes a traveling form that is positioned on the backside of the wall as it is being printed that is equipped with a vibrator to add a smooth finish to the wall and aid with consolidation. After each mix runs through the system, the hopper/auger must be sprayed down and cleaned to ensure product life is maximized and prevent buildup in the system. If a job has to stop mid print, the concrete may be kept from setting by agitating the mix with a Minnich concrete vibrator. A CAD drawing below shows all each component is connected on the hopper/auger combination.



The Control System

The control system consists of both hardware and software elements. The hardware will use a Raspberry Pi, an Arduino Uno, three LIDAR sensors, two rotary encoders, automotive buttons, and a kill switch. The software will include python code that will communicate wall specifications to the control unit, and Arduino code to run the operation of the skid steer and sensors. The Raspberry Pi be tapped into the Controller Area Network (CAN bus) of the skid steer and will act as another control unit in the system that can send CAN messages across the bus, causing the required movements of the skid steer and loader arm. The Arduino will control and monitor the sensors and relay this information to the control box connected to the bus. The control units will be powered by a 12V outlet from the battery in the skid steer. A buck converter will step down the voltage to 5V which is the operating voltage for the RPi/Arduino. It will also protect the system from voltage spikes. A fuse will be used to prevent too much current in case of a short. Since we are trying to electrically operate the vehicle, several safety measures will be in place. During testing, a certified skid steer operator will sit in the cockpit with a kill switch to the Control System. This operator will be able to shut down messages sent to the bus and take over manual operation at any time. Testing will be done in a roped off location outside of the lab. The final design also includes proximity sensors to prevent any collisions.

The Concrete Mix

The concrete mix design is comprised of 9 major components: cement, fly ash, rock (1” max diameter), aggregate (3/8” max diameter), sand, water, nanoclay, citric acid, and daracem 55. All 9 of these components will be mixed together and added to the hopper manually to serve as our printing material. Concrete may be mixed on site as needed to complete the project.

Section III.

	Hazards Inherent to the Project (Check all that Apply)	
	☐Extreme Temperature ☒Electrical Hazard > 50 volts or high current ☒Noise Generated > 85 dBA ☒Sharp Edges ☐Flying Debris or Impact ☐Pressure Vessel/Compressed Gas ☐Bungee Cables/Elastic Energy Storage ☐Fire Hazards (open flame, welding, cutting) ☐Handling Hazardous Materials ☒Dusts/Other Particulate Hazards	☐Heights (roofs, lifts, towers, catwalks, etc.) ☐Potential for Oxygen Deficiency or Other Atmospheric Hazard (i.e. gas, vapor) ☐Storage of Hazardous Materials on site ☐Lithium Batteries ☐Transportation of Hazardous Materials ☐Other: **Equipment Used** ☐Golf Cart/ATV ☒Forklift ☒Tractor

	☐Work in Confined Space (natural or man-made) ☒Falling Objects ☐Trenching/Excavating ☐Explosion	☐Other

Health and Safety Information: Briefly describe the hazards associated with the materials or equipment used during the procedure. (Attach separate sheet of paper if necessary)

1. Electrical Hazard: Electrical energy release associated with the electrical components of the hydraulic pump and of the skid steer. We will follow NFPA 70 for safe electrical design and installation. Proper grounding and a use of a circuit breaker will be utilized for preventative measures. To mitigate risk, avoid water exposure to electrical components and ensure safe plugging/unplugging practices when connecting equipment via the control box (115V power supply connected to circuit breaker).

2. Mechanical Energy Release associated with the mechanical systems of the 3D printer. Pinch points, and failing cables are a potential risk with this system if operated improperly. To mitigate risk, the testing area will be off limits to all individuals, and may only be entered when deactivated. This will be accomplished using visual warnings such as signs and setting perimeters around the test area. Proper PPE for Bert Cooper must be worn.

3. Chemical Contact/Inhalation associated with the mixing of concrete for use in system. The concrete mix has potential to cause burns to the skin and eyes. The raw materials (such as cement and fly ash) have the potential for particulate inhalation. To mitigate risk, proper PPE must be worn at all times. This includes, safety glasses, closed toe shoes, pants, gloves, and an N95 Particulate mask.

4. Hearing Damage associated with the mixing of concrete due to the concrete mixers (about 85 dBa). To mitigate risk, hearing protection such as ear buds is recommended to reduce damage.

5. The only individuals approved to enter the exclusion zone are the operators, mechanic technicians, a designated concrete mix supervisor, and CEAT Faculty/Staff familiar with systems such as Project Champion, Client, and Project Mentors.

PPE Required:
Hard Hat (While in exclusion zone)
Closed Toe Shoes (At all times in Bert Cooper Labs)
Gloves (While in exclusion zone, and mixing concrete)
Long Pants (At all times in Bert Cooper Labs)
Safety Glasses (At all times in Bert Cooper Labs)
Hearing Protection (While mixing concrete)
N95 Particulate Mask (While mixing concrete)

Section IV.

Personal Protective Equipment or Clothing Required: All activities require basic protection including appropriate clothing, hand protection, safety shoes/boots, and eye protection. Any additional PPE requirements based on the hazards identified as part of minimizing risk of exposure, injury or illness. (Check all that Apply)		
☒Face Shields/Safety Glasses ☒Hearing Protection ☒Hard Hat ☒Gloves ☐Fall Protection	☐Respirator Type: Cartridge/Filter Type: ☒N95 Particulate Mask ☐Portable Eye Wash	☐Emergency Shower ☐Extraction Equipment (Confined Space) ☐Other:

Safety Training Required	
☐ Advanced First Aid	☐Confined Space
☐CPR	☐Laser Safety
☐Emergency Action and Preparedness	☒Forklift/Other Heavy Equipment
☐Project Specific Hazard Communication	☒N95 Particulate Mask Disclaimer
☐Compressed Gasses	☐Respiratory Protections
☐HotWorks (Welding, Torch/Plasma Cutting)	☐Fire Extinguisher
☐Ladder	☐Other:

Section V.

Method Procedures: Give a step-by-step instruction for the procedure. (Attach separate sheet of paper if necessary)
Definitions: Mechanics Technicians – individuals responsible for connecting all mechanical systems prior to operation. These technicians are the only individuals that should enter the exclusion zone. For the purpose of this project, our mechanics technicians shall be individuals who are well versed in the mechanical systems of the project, and can easily identify if the equipment is set up properly and is safe for operation.

Concrete Mix Supervisor - individual who is responsible for monitoring the mixing of concrete, and assessing the performance of the concrete during printing operations. They shall identify any issues that arise due to improper extrusion of concrete, collapsed sections of walls, voids created in the hopper, and improper mix practices.

Exclusion Zone – the area designated by black and yellow striped duct tape on the floor. In addition to this tape, orange cones are to be placed around the perimeter of the exclusion zone with a chain connecting each cone. This area is not to be entered during setup/operation of the skid steer, unless the individual is cleared for entry. Additionally, the exclusion zone is not to be entered for any reason during printing operation; the skid steer must be turned off before entrance into the exclusion zone. The exclusion zone shall only be entered by the skid steer operator and the mechanics technicians.

Operating procedure for Concrete mix:

1. Preparing Aggregates
    a. Follow ASTM standards when testing moisture content of each aggregate
    b. Take a small amount of aggregate and weigh
    c. Record measurement
    d. Heat up aggregates to let moisture evaporate
    e. Weigh again and calculate moisture content
    f. Add/remove/do not change amount of water content based on current SSD level of aggregate
2. Weighing
    a. Determine volume of concrete needed by using LxWxH of each wall to be constructed
    b. Use a mix design tool to calculate how much of each mix component will be needed (final mix design still being developed)
    c. Weigh out all aggregates, cement materials, and admixtures as needed
3. Mixing
    a. Dump all aggregates (sand, 1" and 3/8") and half of water into mixer and mix until thoroughly combined
    b. Add in cement materials (fly ash and cement) and rest of water and mix until thoroughly combined
    c. Distribute admixtures into mix (nanoclay, citric acid, and daracem) while mixer is on and mix until thoroughly combined
    d. Turn off mixer and dump mix into wheelbarrow for transportation
    e. Prepare rebar on wall

Operating Procedure for Control System:

1. Before Printing
    a. Connect control unit to USB of a personal computer
    b. Run loader program and enter desired specification for the wall to be printed
    c. Disconnect from the computer and connect the control unit to the automotive connector that is tapped into the CAN bus.

d. Make sure the printing location is clear.

2. During Printing
    a. Sit in the cockpit, fasten the seatbelt and lower safety bar
    b. After skid steer has been started, manually position into the starting location.
    c. Make sure that the kill switch is in the on position.
    d. Hit the start print button.
    e. Monitor the system during the print to make sure everything is on track.
    f. When it is time to reload, hit the pause print button and stop auger.
    g. Manually move skid steer to the location of the supply of concrete.
    h. Press the reload button- the loader arm will lower so you can refill the hopper.
    i. Press the auto-raise button- the loader arm will raise to the last position.
    j. Manually move skid steer back to the last position on the wall.
    k. Press the resume print button to resume auger.
    l. After the print is done, turn off the control unit and manually take over control.

Operating Procedure for Mechanical System:

1. Before Printing:
    a. Add Magic Kote to the surface of the hopper and auger blade to prevent concrete from sticking to the hopper or auger and aiding in cleanup
    b. Mark off exclusion zone
    c. Lower the system to the ground
    d. Pour the mix into the hopper
    e. Ensure that printing area is cleared
    f. Move skid steer into starting position
    g. Raise hopper to desired starting height
    h. Start motor and begin printing
2. During Printing
    a. Refill hopper with concrete when prompted
3. After Printing:
    a. Turn off motor and disconnect from power
    b. Remove excess concrete from hopper
    c. Remove auger blade from hopper
    d. Wash the concrete out of the hopper and dispensing system
    e. Place printer into desired storage location

Section VI.

Waste Disposal Procedure: Give a step-by-step instruction for the procedure (if applicable). (Attach separate sheet of paper if necessary)

The only waste that may be created during the process is excess concrete. The current procedure for disposing of this waste is as follows:

1. Dumping any excess concrete onto a pile behind Bert Cooper Labs
2. After the pile is large enough to fill a dump truck, the pile will be broken up by a skid steer
3. Once broken up, the material is placed into a dump truck to be hauled off to an appropriate dump location

In an effort to increase sustainability, this excess material may alternatively be repurposed and used to fill large potholes in gravel roads.

Section VII.

First Aid Procedures: Give a step-by-step instruction for the procedure. (Attach separate sheet of paper if necessary) This section should also contain the address and location(s) that the SOP will be used.

All incidents require that as soon as possible the Instructor of Record and Profession Staff over lab be notified.
Location: 1812 W Tyler Ave, Stillwater, OK 74075 (North side of building)
 	
Location of Nearest Hard Phone Line: Cooper Lab front office
Nearest Location of a solid Cell phone signal: Good signal throughout building
Emergencies:
● One person is assigned to stay with the injured personal
● One person should be assigned to call 911, this person will stay on the phone and state the following
    o Location of the accident (This should include building and room)
    o Type of injury
● One person should be assigned to escort the emergency response crew to the location
 	
Specialized First Aid Procedures as related to this project:
For any safety incident, immediately contact a facility supervisor/faculty member or EMS.
Concerning Concrete Exposure:
1. If cement/fly ash particulate is inhaled, immediately seek medical attention.
2. If skin is exposed to wet concrete, wash immediately with soap and water. If chemical burn ensues, seek medical attention.
3. If eyes are exposed to cement/fly ash particulate, or wet concrete, immediate flush eyes at eyewash station. If symptoms do not recede, seek medical attention.
Concerning Cuts/Lacerations/Pinches/Other Trauma from Mechanical Components:
1. Seek out first aid kid, and apply appropriate first aid depending on type of injury and severity. For serious injury, seek medical attention or contact EMS.
Concerning Electrical Shock:
1. If an individual has experienced electrical shock, ensure environment is safe to approach the individual.
2. Only touch the individual if you are certain the electrical supply is no longer connected to them.
3. If no heart-beat is present, contact EMS and perform CPR if certification is still valid.
4. For electrical burns, dress wound and seek medical attention.

Section VIII.

Spill/Release Containment, Decontamination, and Clean-up Procedures: Give a step-by-step instruction for the procedure (if applicable). (Attach separate sheet of paper if necessary)
The only potential for spills that may be created during the operation of this system is the concrete mixture and its individual raw components prior to mixing. The current process for containing and cleaning up these materials is as follows: 1. Raw materials are stored outside of Bert Cooper Labs in large piles, and are brought into the facility in 5 gallon buckets as needed 2. In the event of a raw material spill (such as sand or aggregate), it will be scooped up and reused or disposed of in the waste pile 3. In the event of a concrete mixture spill, water will be sprayed on the concrete mixture to wash it away. There are no current required decontamination practices. Per Section II: Procedure Overview, it will be necessary to spray the entire mechanical system down (tracks, rails, hopper/auger, etc.) with water to ensure that no concrete dries and jeopardizes the integrity of the system.

Section IX.

Approvals Required: Describe any special approvals required before conducting this work such as approval by Principal Investigator or lab supervisor before beginning work (if applicable). (Attach separate sheet of paper if necessary)
Approval of Bert Cooper Lab Supervisor to operate equipment Approval of Electrical Systems for Energization by authorized CEAT personnel

Section X.

Designated Area/Communications: (For work involving particularly hazardous dangers, identify the area where the work will be conducted and to where it will be confined; identify any communication that will be done to assure others know the hazards and location of this work.) (if applicable). (Attach separate sheet of paper if necessary)
N/A

Section XI.

Piping, Wiring, and Instrumentation diagram: (This should include a detailed schematic illustrations of the functional relationship of piping, instrumentation and system equipment components. (Attach separate sheet of paper if necessary)