BIOINSPIRED DESIGN OF NOVEL REINFORCED CONCRETE ELEMENTS

A Major Qualifying Project Report

Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

Robert Ciotti

Simone Williams

18 March 2021

Advisor:

Assistant Professor Nima Rahbar

ABSTRACT

Concrete has the greatest, most wide-spread usage of any construction material. However, cracking and deterioration remains a prominent issue with this material. This project researched the feasibility of reinforcing concrete with aluminum foams and stainless-steel fibers. 10 PPI, 20 PPI, and 40 PPI 6106-T6 aluminum foams and stainless steel A16 fibers were used as reinforcement in 1” x 1” x 1” cubes of cement paste and cured for 14 days before tested in compression. The goal of this project was to evaluate whether these reinforcement materials have positively reinforced the cement, and whether changing the composite structure can yield a stronger concrete material.

EXECUTIVE SUMMARY

Introduction

Concrete has the greatest, most wide-spread usage of any construction material. For the past seven years, the globe has demanded the production of over four billion metric tons of concrete annually (Statistica 2020). Yet despite its popularity, cracking and deterioration remain a prominent issue with this material. Reinforced concrete exists to combat the cracking tendencies concrete has by placing rebar in areas where tension and cracking would be expected. Even so, the rusting of rebar ruins the durability of concrete. Metal foams and fibers are an emerging alternative to these issues. This project will conduct research into the feasibility of reinforcing concrete with aluminum foams and stainless-steel fibers. This will be completed by creating 1” x 1” x 1” cubes of cement paste reinforced with these materials. These composite cubes will then be tested to evaluate whether the change has positively reinforced the cement.

Background

Reinforcing cement with aluminum foams and steel fibers and creating a new composite structure for concrete would be huge for the future development of high performing concrete. While traditional reinforced concrete has been an important and long-trusted building material, there exists other reinforcing materials that can possibly yield better mechanical properties for concrete. Moreover, the concept of reinforced concrete is promising, but there still exists a discouraging number of structural issues with rebar and other metal barring used to strengthen cement. The issue with reinforced concrete is that the addition of steel ultimately ruins the durability of concrete. When moisture enters the cracks of concrete, an electrochemical reaction forms, creating a battery-like condition where the steel begins to rust. Rusting can cause for the rebar to expand up to four times its size, making already formed cracks larger and causing spalling, or flaking with the concrete (McCartney 2016; Slowik 2019). This ultimately leads to the mechanical failure of the concrete.

From examples in nature, man has developed metallic foams, which take the design from the foams and bubble formation, and use a stronger material – typically aluminum, nickel, copper, or steel – to produce an incredibly strong, low-density material. Metallic foams are divided into two classifications: open-cell and closed-cell (Ranut et al 2014). Open-cell metallic foams serve as a perfect composite material to combine with concrete. The interconnected cells allow for concrete and other fine aggregates to combine with the foam to create an effective reinforced material composite.

Following the industrial revolution that brought forth many of the mass production methods we see today, the Dobeckmun Company aimed to mass produce a new reinforcing material known as stainless-steel fibers. This fiber material would soon serve as a popular reinforcement to various industrial materials due to its excellent mechanical properties including high-thermal corrosion resistance, and high electrical and thermal conductivity. Thus, metal fibers serve as a perfect complement to compensate the weaknesses of concrete and form a composite material with superior mechanical and chemical properties.

Methodology

The first step was to determine the appropriate water to cement (w/c) ratio for the cement paste. This step was important to figure out what ratio would produce a mix that would go through and fill the pores of the aluminum foam. A test sample was used in order to determine the necessary mix as to not waste any future samples needed for this research. A 0.4 w/c was created but was, however, too viscous and did not seep into any of the pores; it remained in a layer on top. The same procedure was attempted using a 0.5 w/c mix and it was fluid enough to go through the pores of the foam. 0.5 w/c ratio was concluded to be the best mix for the reinforcing materials.

Next, 1” x 1” x 1” (2.54 cm x 2.54 cm x 2.54 cm) cubes were made as five different test groups: control, 10 PPI (pores per inch), 20 PPI and 40 PPI aluminum foam, and steel fiber. Duocel foams Aluminum 6101-T6 foam were used, and all samples were medium (8-10%) density. Intramicron stainless steel A16 fibers of 30 μm in diameter and 20 mm long were used.

The cube foam samples were placed into a cup of cement paste, placed in a mold and left on a vibrating table for 10 minutes to get rid of all the air bubbles. For the samples reinforced with steel fibers, the fibers were added to a mold with 0.5 w/c cement paste. The control samples were made with a standard 0.5 w/c mix. All samples were left to cure in a curing room for 14 days.

The samples were tested in compression using the Instron machine accessible in the WPI Kaven Hall Structures Lab. The control and fiber reinforced samples were tested until failure. The foam reinforced samples were tested until they were compressed by 75% of their original height. The data collected was used to compare each test group and determine the best reinforcing option for concrete.

Results and Discussion

The control samples had an average ultimate strength of 3348.12 psi (23.1 MPa). All of the control samples had type 2 or 3 failure.

Because the aluminum foams do not reach a failure point – they will continually compress until completely flattened – the samples were tested until they were compressed by 75%. If the test were not stopped, the samples could continue to plastically deform. The aluminum foam of all porosities were compressed greatly, beginning to crumble apart under the load, with the exception of the 20 PPI foam-cement paste samples, which did not crumble. At the end of testing, because of the plastic behavior of the aluminum foam, the samples were able to withstand high stresses.

The yield compressive strength of the 10 PPI foam-cement paste samples averaged out to be 3363.25 psi (23.2 MPa). At the yield point, the foam samples performed better under compression than anticipated, but also, they performed similarly to the control samples. The average maximum compressive strength of the samples between strain values 0.15 to 0.3 was 2568 psi (17.7 MPa). The theoretical compressive strength of this aluminum-cement paste composite should be about 2948 psi (20.3 MPa). The actual compressive strength was about 2568 ksi (17.7 MPa), meaning there was a 14% increase in yield behavior but 30% decrease in maximum strength.

The yield compressive strength of the 20 PPI foam-cement paste samples averaged out to be 778 psi (5.43 MPa). At the yield point, the foams performed much worse compression than anticipated. The reason as to why is very uncertain. The average maximum compressive strength of the samples between the strain values 0.1 to 0.3 was 1238 psi (8.53 MPa). The theoretical compressive strength of this aluminum-concrete composite should be about 2983 psi (20.6 MPa). The actual compressive strength was about 1238 (8.53 MPa), meaning there was a 73.6% decrease in yield behavior and 169% decrease in maximum strength.

The 40 PPI foam-cement paste samples had an average yield strength of 1885.4 psi (13 MPa) just before a strain of 0.05. The average maximum compressive strength of the samples between the strain values 0.15 to 0.3 was 1156 psi (7.97 MPa). The theoretical compressive strength of this aluminum-concrete composite should be about 2968 psi (20.5 MPa). The actual compressive strength was about 1156 psi (7.97 MPa). These composites were 57% weaker yield in strength than the control and 10 PPI samples.

The steel fiber reinforced samples ultimately failed with cracking occurring from top to bottom, unsurprisingly indicating the stress of the vertical compressing force, similar to the control samples. The fibers rely on their greater material strength coupled with the rigid and stabilizing nature of the concrete around them to produce a superior composite. The steel fiber samples had an average compressive stress of around 2909.17 ksi (20 MPa). These composites possess a weaker yield strength than the 10 PPI and control samples, but stronger than the 20 and 40 PPI.

Conclusion

Cement paste composites made with metallic foams and fibers were engineered to combine the structural properties of both materials and produce a composite with exponentially superior properties relevant to its intended usage, in our case, compressive and yield strength. From our results, and the material properties of the components used, we can conclude that by combining aluminum foams of varying porosities with cement paste with a 0.5 water to cement ratio, a composite can be produced that exhibits a yield strength significantly superior to that of traditional reinforced concrete. Furthermore, yielding greater compressive strength than the material properties of either foam or concrete components would naturally produce. This implies that the structural design of the composite provides an additional advantage to the material properties of the composite. These design applications could span beyond reinforced concrete, and future research should be conducted on alternative material components to be used within concrete composites, that serve as a cheaper reinforcement without sacrificing compression strength.

ACKNOWLEDGEMENTS

This project would not have been accomplished without the resources and opportunities provided to us by Worcester Polytechnic Institute (WPI). We would especially like to thank one of the lab managers for Kaven Hall, Russ Lang, for his unwavering assistance with purchasing materials for this project and prepping the materials for use; PhD student Shuai Wang for his help with testing and imaging our samples; and lastly, our project advisor, Assistant Professor Nima Rahbar, for remotely advising and helping us conduct this project during a very uncertain and difficult time.

AUTHORSHIP

Abstract: Simone Williams

Executive Summary: Robert Ciotti and Simone Williams

Acknowledgements: Simone Williams

Capstone Design Statement: Robert Ciotti

Professional Licensure Statement: Simone Williams

Introduction: Simone Williams

Background: Robert Ciotti and Simone Williams

Methodology: Simone Williams

Results and Discussion: Robert Ciotti and Simone Williams

Aluminum Foam Reinforced Cement Paste Composite in Building Design: Simone Williams

Conclusion: Robert Ciotti

CAPSTONE DESIGN STATEMENT

The Bioinspired Design of Novel Reinforced Concrete Elements project satisfies the Worcester Polytechnic Institute Civil Engineering Capstone Design requirement for a Bachelor of Science degree with its design of a structure utilizing the alternative materials developed in this project.

Economic

The real-world costs of this project were incurred by the materials used to construct the reinforced concrete samples. These samples were then tested, and their material properties observed and calculated to incorporate as a custom material on the RISA design platform. The material was observed to provide a stronger supporting strength when serving as a member in place of concrete. This should reduce the need for member quantity, as well as member size. These reductions will also yield a decrease in financial investment when applying the material to real-world structures.

Environmental

Just as the reduced need for concrete material will yield a reduction in material costs, it will similarly yield a reduction in the total negative environmental impact due to the incorporation of the developed reinforced materials. In conjunction with material presented in *ES 2800 – Environmental Impacts of Engineering Decisions*, it was emphasized that in order for cement to be produced, it must be heated to extremely high temperatures, which results in a considerable amount of carbon emissions. The reinforced concrete alternative not only reduces the need for cement and its harmful carbon emissions but presents an opportunity to use recycled aluminum as the augmenting agent in the material, which better contributes to a circular value chain with lesser harmful environmental impacts.

Constructability

By applying concepts learned in *CE 2002 - Introduction to Analysis and Design* and *CE 3008 – Design of Reinforced Concrete Structures*, the RISA design platform was utilized to present a real-world application of the materials developed in this Major Qualifying Project. The constructability was assessed by designing a self-supporting structure out of traditional structural steels, and then replacing said members with the reinforced concrete developed in the project. The structure was then reevaluated with the alternative material, and the columns were redesigned with minimum dimensions to still provide equivalent support. This redesign allows for cheaper procurement of members, fabrication, and less initial material costs.

Ethics/Social

Though such a promising alternative to reinforced concrete could provide potential shifts in supply and demand chains in both steel and concrete industries, it was determined that the yield strengths of the alternative material combined with other products available in the rapidly growing field of reinforced concretes, the material designed in the project is not expected to carry a significant weight to sway industries to an extent that would propose ethical or social concerns.

PROFESSIONAL LICENSURE STATEMENT

In order to become a licensed professional engineer, one must go through extensive training and testing. Professional engineers (PE) are the ones who “may prepare, sign and seal, and submit engineering plans and drawings to a public authority for approval, or seal engineering work for public and private clients” (NSPE, n.d.). Being a professional engineer gives one a higher level of responsibility and respect from their colleagues.

To become a licensed engineer, one must earn a four-year degree in engineering from an Accreditation Board for Engineering and Technology (ABET) accredited university. Upon completion, they should take the Fundamentals of Engineering (FE) exam to receive an Engineer-in-Training (EIT) certification. The FE exam is administered by the National Council of Examiner for Engineering and Survey (NCEES) and tests a comprehensive range of subjects in engineering; it can be taken nationwide. Once certified, one should complete four years of engineering experience under a PE. Lastly, take the Principles and Practice of Engineering exam in their respective state of practice (NSPE, n.d.).

The work done in this project would need the stamp of approval from a PE if the simple design created were to be made with aluminum reinforcement. Additionally, the use of the reinforced material made and tested in this project would need the approval from a PE in the Civil field or another field (i.e., Architectural).

TABLE OF CONTENTS

TABLE OF TABLES

TABLE OF FIGURES

1. INTRODUCTION

Concrete has the greatest, most wide-spread usage of any construction material. For the past seven years, the globe has demanded the production of over four billion metric tons of concrete annually (Statistica 2020). Yet despite its popularity, cracking and deterioration remains a prominent issue with this material. Reinforced concrete exists to combat the cracking tendencies concrete has by placing rebar in areas where tension and cracking would be expected. Even so, the rusting of rebars ruins the durability of concrete. Metal foams and fibers are an immerging alternative to these issues. Additionally, creating a composite structure using foams and fibers can create a stronger and more ductile concrete material.

Reinforcing concrete with steel was a crucial development in the 17th century (Vale 2017). However, it is not as common to reinforce concrete with other metals, though many alternative materials for concrete reinforcement such as stainless steel, aluminum, aluminum bronze, and fiber polymers exist as practical options. Reinforcing concrete reduces the brittleness of concrete and increase its strength. The compressive strength of concrete (cured for 28 days) ranges from 2500 psi to 10,000 psi (17 MPa to 70 MPa) depending on the application, but average is about 2959 psi (20.4 MPa) (NRWCA n.d.; Slowik 2019). When traditionally reinforced with rebar, the compressive strength is around 5076 psi (35 MPa) (Slowik 2019).

Metal foams have a porous, but closed cellular microstructure, which allows for it to have its effective thermal conductivity and permeability as well as decent stiffness and strength (Ramamurty and Paul 2004). The unique nanostructure of metal foams could be a solution to the cracking and shear failure that occurs with traditional concrete. However, the mechanical properties of metal foams greatly depend on the porosity of the foam, which is directly connected to its density (Ramamurty and Paul 2004). Thus, foams of different porosities will be tested. Aluminum will be used as it has great corrosion resistance and is a very ductile metal.

Metallic fibers are another concrete structural supplement that will be tested in addition to metallic foams. Metallic fibers – more specifically steel fibers – have been in frequent use of the friction industry, and more recently as a metal reinforcement in certain materials, including brake pads, non-asbestos matrices, and for our purposes, concrete composites (Dante 2016). Steel fibers are a favorable reinforcement to use, due to their ability to increase the load-bearing capacity of concrete, reduce slab thickness, keep cracks from diminishing load capacity, increase durability, reduce maintenance costs, improve flexural properties, reduce water absorption, and increase impact and abrasion resistance (Rodriguez 2019). These potential benefits and more will be tested to observe their effectiveness.

This project will conduct research into the feasibility of reinforcing concrete with aluminum foams and stainless-steel fibers. This will be completed by creating 1” x 1” x 1” (2.54 cm x 2.54 cm x 2.54 cm) cubes of cement paste reinforced with these materials. These composite cubes will then be tested to evaluate whether the change has positively reinforced the concrete, and whether changing the composite structure can yield a stronger concrete material.

2. BACKGROUND

Reinforcing concrete with aluminum foams and steel fibers and creating a new composite structure for concrete would be huge for the future development of high performing concrete. While traditional reinforced concrete has been an important and long-trusted building material, there exists other reinforcing materials that can possibly yield better mechanical properties for concrete. This chapter will discuss some properties of traditional reinforced concrete and aluminum as well as discuss what other researchers have been able to do with metal foams and fibers.

2.1 Typical Reinforced Concrete

Reinforced concrete is the addition of steel bars to concrete to add strength. The main purpose of reinforcing concrete is to protect against brittle failure (Slowik 2019). Its usage became popular in the 19th century and reinforced concrete construction boomed in the 20th century as 20th century engineers thought that reinforced concrete structures would last an extremely long time (Vale 2017; McCartney 2016). Reinforced concrete is mostly used for the creation and construction of slabs, walls, beams, columns, foundations, and frames. It can exist as precast or cast-in-place. Precast simply means the concrete was cast in a mold and cast-in-place means that concrete was cast on the site in which it was going to be used.

A benefit of using reinforced concrete is that its usage speeds up construction time as less concrete is used to make the building material (McCartney 2016). Additionally, the coefficient of thermal expansion for concrete ($10 \times 10^{-6}/°C$) is similar to that of steel ($13 \times 10^{-6}/°C$), so it eliminates large internal stresses due to thermal expansion or contraction (McCartney 2016). Moreover, concrete’s alkalinity can inhibit corrosion as hardened concrete forms a passivating film on the surface of steel (McCartney 2016).

The issue with reinforced concrete is that the additional of steel ultimately ruins the durability of concrete. When moisture enters the cracks of the concrete, an electrochemical reaction forms, creating a battery-like condition where the steel begins to rust. Rusting can cause for the rebar to expand up to four times its size, making already formed cracks larger and causing spalling, or flaking with the concrete (McCartney 2016; Slowik 2019). This ultimately leads to the mechanical failure of the concrete.

2.2 Metal Foams and Fibers as an Alternative Reinforcement

The concept of reinforced concrete is promising, but there still exists a discouraging number of structural issues when it comes to rebar and other metal barring used to strengthen cement. To find a superior material, we look to nature for inspiration. Wood, bones, and sea sponges are all lightweight cellular materials that naturally exhibit considerable structural properties. This is possible from these materials by producing a design through bubble formation, which creates a porous foam material which increases the strength per mass of the material substantially (Garcia-Moreno 2016).

From these examples in nature, man has developed metallic foams, which take the design from the foams and bubble formation, and use a stronger material – typically aluminum, nickel, copper, or steel – to produce an incredibly strong, low-density material. Metallic foams are divided into two classifications: open-cell and closed-cell (Ranut et al. 2014). An example of each can be seen below in Figure 1.

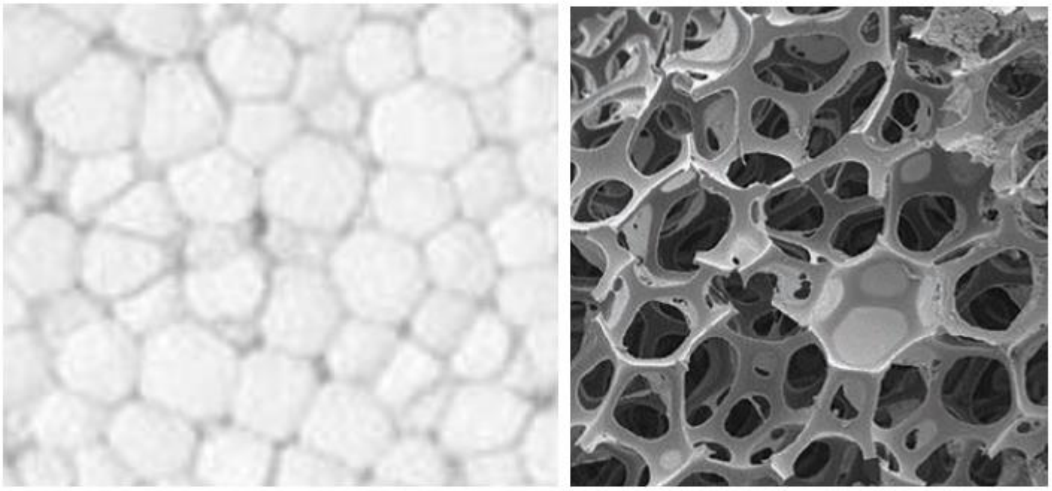


Figure 1: Closed-Cell Insulation (Left) vs. Open-Cell Insulation (Right) (Acoustic Fields 2019).

As is visually evident by the figure above, open-cell metallic foams have their flow paths interconnected, while closed-cell figures have their cells (bubbles) encased, and therefore largely inaccessible from other cells. It is the accessible open-cell metallic foams that serve as a perfect composite material to combine with concrete. The interconnected cells allow for concrete and other fine aggregates to combine with the foam to create an effective reinforced material composite.

While the development of metallic foams remains a relatively new innovation in the world of material micro design, there exists evidence of the usage of metal fibers some 3000 years ago, where gold and silver were hammered into thin sheets, then cut into fine strips. These unique presentations of valuable metals were mostly used for elegant decoration, yet the reinforcing properties possessed by these refined adornments would not be fully realized until 1946. Following the industrial revolution that brought forth many of the mass production methods we see today, the Dobeckmun Company aimed to mass produce a new reinforcing material known as stainless-steel fibers. This term “fiber” officially refers to thin metal objects with diameters of one micron to 100 microns. Objects with larger diameters are referred to as wires (Küster et al 2018).

This fiber material would soon serve as a popular reinforcement to various industrial materials due to its excellent mechanical properties including high-thermal corrosion resistance, and high electrical and thermal conductivity. When used as a composite, reinforcing material in concrete however, the important properties to consider are their high tensile strength, high elastic modulus, high thermal resistance, and high elongation at break (Küster et al 2018). Possibly the most important feature of metal fibers would be its high tensile strength. While concrete slabs exhibit fantastic compressive strength, their tensile strength is disproportionately weaker. Thus, metal fibers serve as a perfect complement to compensate the weaknesses of concrete and form a composite material with superior mechanical and chemical properties.

2.3 Other Works vs. Ours

There has been a variety of research done analyzing and evaluating steel foam or composite foams within concrete. Bai and Davidson in 2014 developed “foam insulated concrete sandwich structures (ICSP)” where they “sandwiched” a foam panel in between two slabs of concrete. They tested various existing composite theories and tested the best one that aligned with their discrete models. When conducting deflection testing on the ICSP, they found that the solutions to the theories they tested yield the same predicted deflection and shear deformation results.

Prabha et al in 2017 tested the behavior of steel foam concrete composite (SFCC) panels under in-plane lateral load. A SFCC panel is “steel sheets as the outer skin with foam concrete infill […] connected together by using through-through mild steel studs” (Prabha et al 2017).

They tested SFCC panels under static and cyclic loading and found that the steel studs that connect the panel caused for its failure by yielding the steel sheets. This caused for the panel to buckle under static loading and tear under cyclic loading. Eltayeb et al. conducted a similar experiment in 2019, except they also tested rubberized concrete as the infill material. They found that the foam rubberized panels had higher ductility but also a larger number of cracks in comparison to the control foam concrete sample they also tested.

Lastly, Van Zijl and Van Rooyen in 2018 evaluated the feasibility of developing reinforced foam concrete as a structural material. They used lightweight foam concrete reinforced with steel in a structural walling system to see whether it can be used structurally. They found that the addition of microfibers allowed for the material to have restrained shrinkage cracks, meaning that corrosion would be slowed down.

As can be seen, there has been a large amount of research done relating to foam concrete or foam reinforced concrete, but none like what is being attempted with this research. Steel has been a common material used when evaluating the use of foam in concrete given how well it has worked for the past 500 years in reinforced concrete. Though, there have not been many other metals used as foam options. This project is looking into use of aluminum because it has excellent corrosion resistance, a compressive strength of around 4351 psi (30 MPa), low density (around 2.70 g/cm^3), lighter than steel, and non-adsorptive (Davis 1999; AZoM 2002). Aluminum fibers are not as commonly found so this project will be utilizing steel fibers. Due to their lower structural properties, the usage of aluminum fibers is sparce. Given steel fibers' superior structural properties yet still inexpensive cost, steel is the favorable material to use for reinforcing fibers.

3. METHODOLOGY

3.1 Determine Mix Ratio

The first step was to determine the appropriate water to cement (w/c) ratio for the concrete mix. No aggregate was used in this mix as it would be too large to go through the pores of the aluminum foam samples. This step was important to figure out what ratio would produce a mix that would go through and fill the pores of the aluminum foam. A test sample was used in order to determine the necessary mix as to not waste any future samples needed for this research.

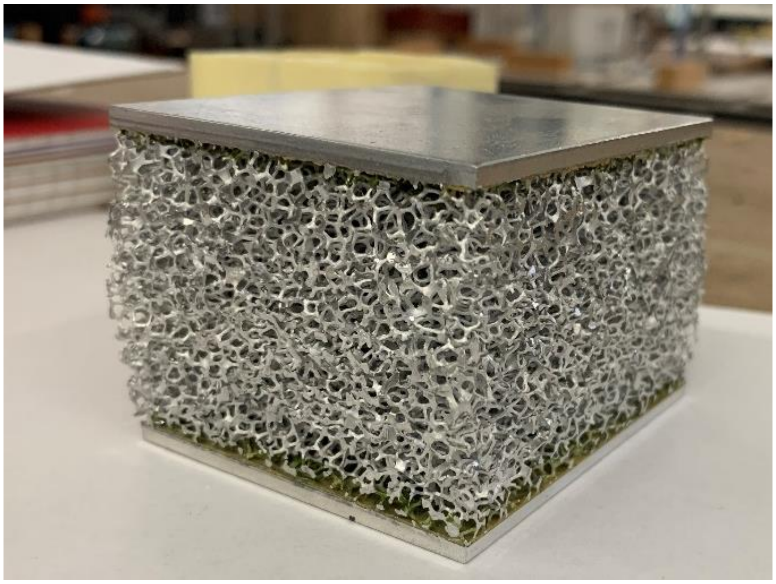


Figure 2. Aluminum foam sample used as a test.

First a 0.4 w/c ratio was tested on an aluminum foam sample provided by Dr. John Obayemi, an Associate Research Professor in the Mechanical Engineering Department at Worcester Polytechnic Institute (WPI). Figure 2 shows an image of the foam sample used. The foam sample was measured and weighed and placed into a custom cardboard mold as it was too irregularly shaped for the molds accessible at the Kaven Hall laboratories at WPI. 40 g of water was added 100 g of sieved cement and mixed until all cement particles were hydrated. The foam sample was placed into its mold and onto a vibrating table. The cement paste was poured onto the top of the foam, however, was too viscous and did not seep into any of the pores; it remained in a layer on top. The same procedure was attempted using a 0.5 w/c mix and it was fluid enough to go through the pores of the foam. 0.5 w/c ratio was concluded to be the best mix for the reinforcing materials that will be used for this research.

3.2 Making of Samples

1” x 1” x 1” (2.54 cm x 2.54 cm x 2.54 cm) cubes were made as five different test groups. Table 1 shows the test groups and how many cube samples were made for each. The reinforcing options that were tested reinforcement with stainless steel fibers and aluminum foam of varying porosities. Duocel foams Aluminum 6101-T6 foam were used, and all samples were of medium (8-10%) density (Figure 3). Intramicron stainless steel A16 fibers that were 30 μm in diameter and 20 mm long were used (Figure 4).

Table 1. Sample Test Groups

Reinforced with	**Number of Cubes**
None (Control)	15
Steel fibers	12
Aluminum foam (10% porosity)	12
Aluminum foam (20% porosity)	17
Aluminum foam (40% porosity)	12

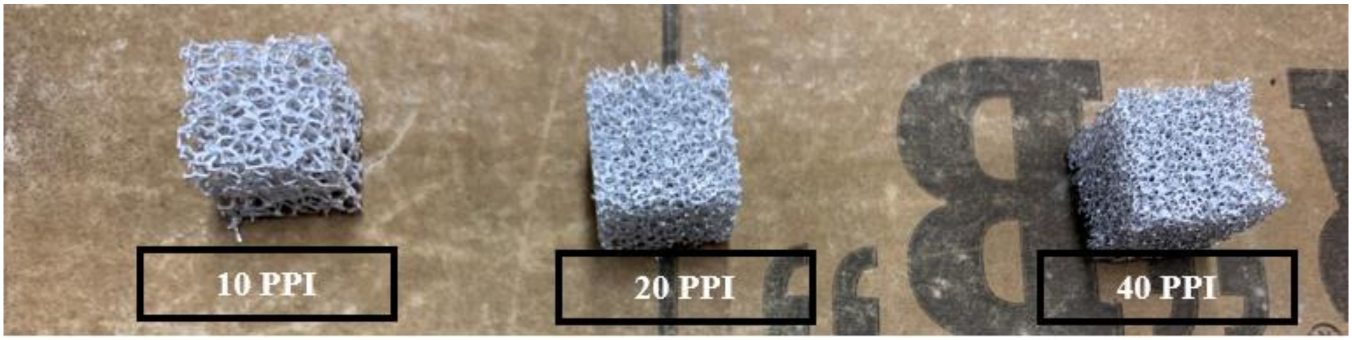


Figure 3. Image of aluminum foam samples cut into 1” x 1” x 1” cubes.

With the aluminum foam, the 1” x 1” x 1” (2.54 cm x 2.54 cm x 2.54 cm) cube foam samples were placed into a cup of cement paste, placed in a mold and left on a vibrating table for 10 minutes to get rid of all the air bubbles. For the samples reinforced with steel fibers, the amount added was reduced based on the volume fraction of the aluminum foams and the strength ratio of aluminum to steel, which amounted to be about 0.6g of fibers per cube. The control samples were made with a standard 0.5 w/c mix. All samples were left to cure in a curing room for 14 days.

Figure 4. Image of steel fibers

3.3 Compression Experiments

Once the 14 days were reached, the samples were tested in compression using the Instron machine accessible in the WPI Kaven Hall Structures Lab. When tested on this machine, a steady and increasing force was applied until the sample fails. Figure 5 shows an image of the testing set up. The control and fiber reinforced samples were tested until failure. The foam reinforced samples were tested until they were

Figure 5. Compression Testing Set-up on the Instron

compressed by 75% of their original height. This is because those samples were not going to reach a yield or fracture point. The data collected was used to compare each test group and determine the best reinforcing option for concrete.

4. RESULTS AND DISCUSSION

Compression testing occurred after each sample had cured for exactly 14 days. Testing was conducted using the Instron machine in Kaven Hall Laboratories at WPI. Below are the compression results for the samples tested. Table 2 shows the average maximum compressive strengths of the samples.

Table 2. Average Maximum Compressive Strengths of the Samples

Sample	**Max Comp Strength. (psi)**
Control	3348.12
10 PPI foam	2568
20 PPI foam	1238
40 PPI foam	1156
Steel fibers	2909.17

4.1 Control Cement Paste Samples

The fifteen control samples had an average ultimate strength of 3348.12 psi (23.1 MPa) (Table 2). Figure 6 shows the fracture and failure patterns of the control samples. All of the control samples had type 2 or 3 failure. Figure 6 shows the fracture pattern of the samples. Type 2 failure is where there is vertical cone on one end of the concrete and vertical cracks running through, stopping at the tip of the vertical cone. Type 3 fracture is columnar cracking through both ends of the concrete.

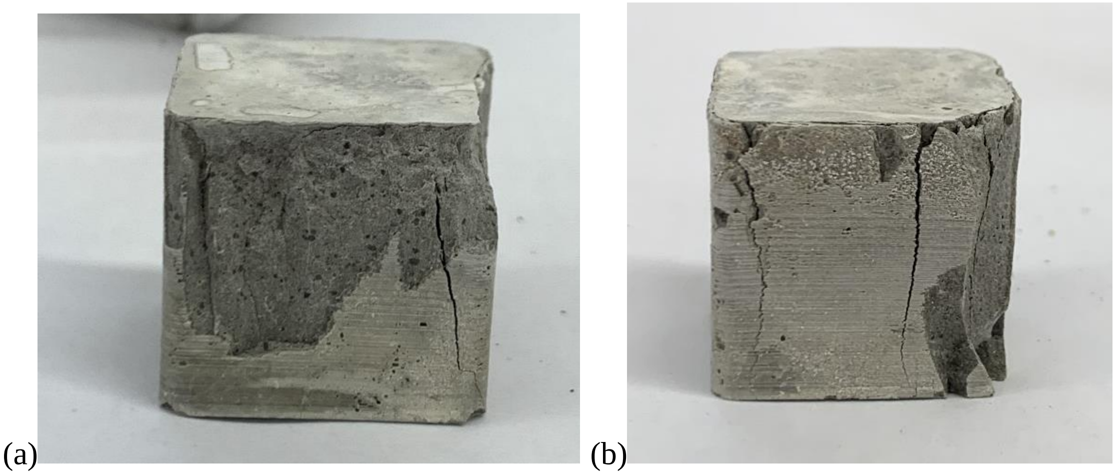


Figure 6. Failure patterns of the control samples: (a) Type 2 fracture, (b) Type 3 fractures.

4.2 10 PPI Foam-Cement Paste Samples

Figure 7 shows the stress vs. strain plot for all twelve samples tested under compression. Because the aluminum foams do not reach a failure point – they will continually compress until completely flattened – the samples were tested until they were compressed by 75%. If the test were not stopped, the samples could continue to plastically deform. Figure 8 shows how the samples looked after testing was stopped. The aluminum foam was compressed greatly, beginning to crumble apart under the load.

On the plot, around 0.05 strain, there is a slight bump in all the lines, before the stress shoots up exponentially. That bump in the plot is the yield stress of the samples. It is where the concrete in the sample begins to yield and the strength of the sample is heavily contingent on the aluminum foam. The yield compressive strength of the 10 PPI-cement paste samples averaged out to be 3363.25 psi (23.2 MPa), with the highest being 4247 psi (29.8 MPa) and the lowest 2746 psi (18.9 MPa). At the yield point, the foams performed better under compression than anticipated, but also, they performed similarly to the control samples.

The maximum compressive strength of the samples was determined by finding the maximum value in the plot where the stress begins to plateau (see Figure 7). This area was between the 0.15 to 0.30 strain range. The average maximum compressive strength of the samples was 2568 psi (17.7 MPa) (Table 2). The values ranged from 3352 (23.1 MPa) to 2240 psi (15.4 MPa). The average ultimate compressive strength of the samples until the test stopped was 35,530 psi (255 MPa) (Table 2). The highest ultimate compressive strength was 56,188 psi (387.4 MPa) and the lowest was 21,228 psi (146.8 MPa).

The aluminum foam occupied 12.4% of the volume of the whole aluminum-cement paste sample. According to the ERG aerospace corporation, their aluminum foams (of all porosities) have a compressive strength of 367 psi (2.53 MPa). Using volume fractions, the theoretical compressive strength of this aluminum-cement paste composite should be about 2948 psi (20.3 MPa). The actual compressive strength was about 2568 psi (17.7 MPa), meaning there was a 14% increase in yield behavior but 30% decrease in maximum strength. At the end of testing, because of the plastic behavior of the aluminum foam, the samples were able to withstand high stresses.

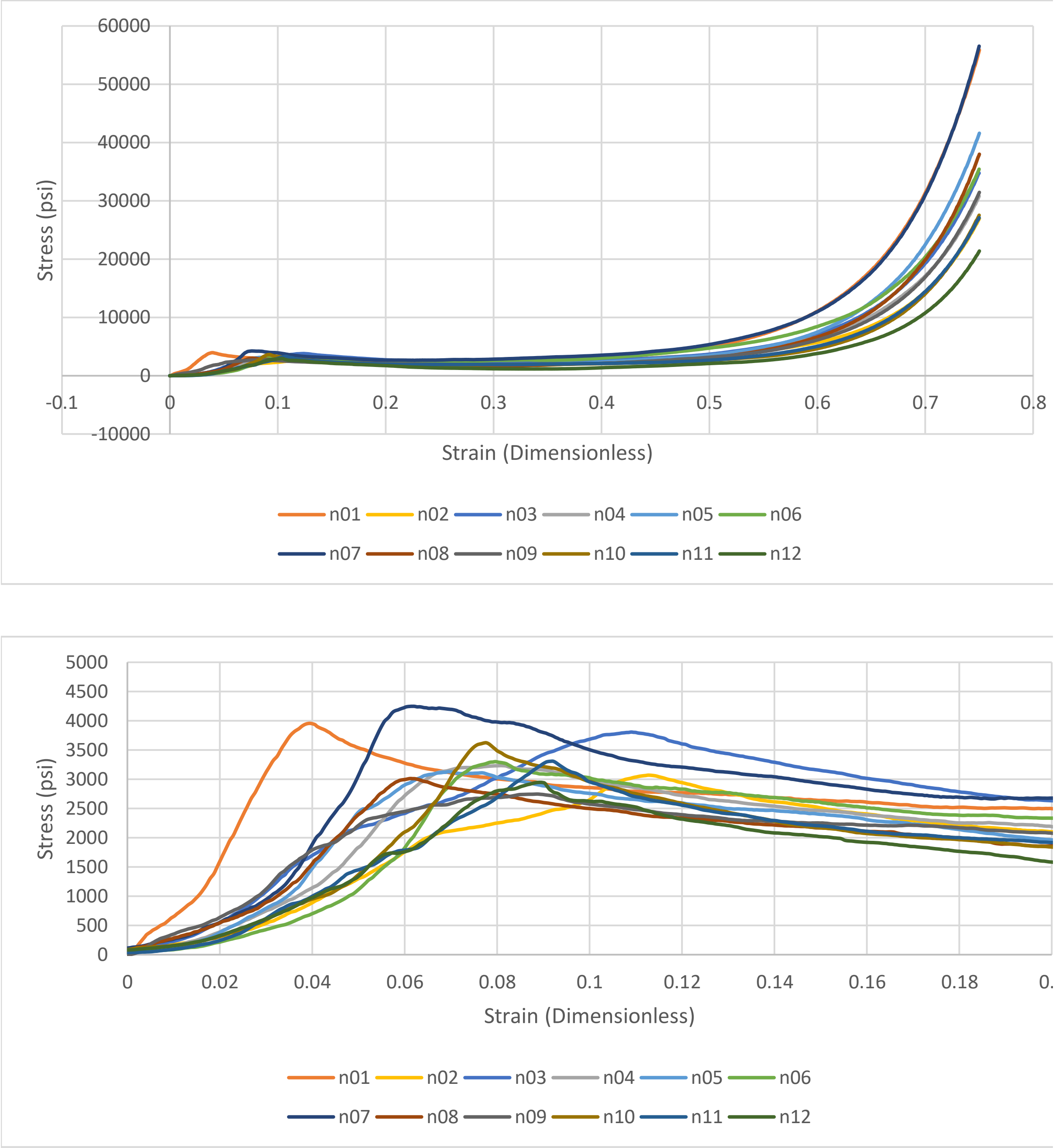


Figure 7. Stress vs. Strain plot of 10 PPI-cement paste samples.

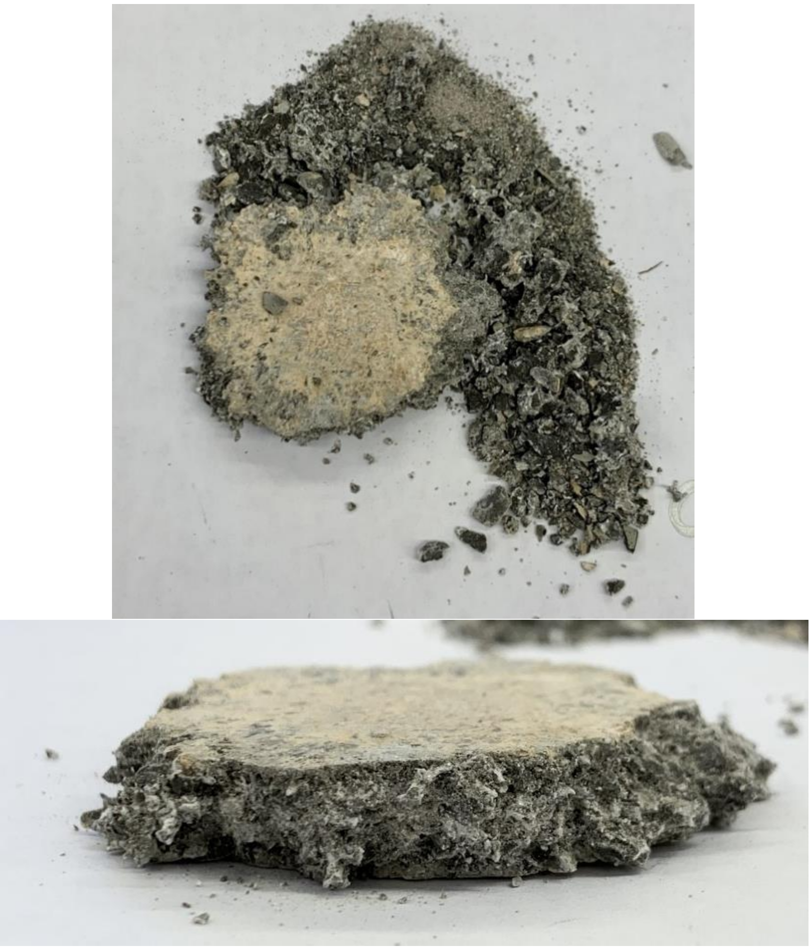


Figure 8. "Failure" of the 10 PPI-cement paste samples.

4.3 20 PPI Foam-Cement Paste Samples

Figure 9 shows the stress vs. strain plot for all 20 PPI aluminum-cement paste composite samples tested under compression. Initially, 12 were tested like with the samples of 10% and 40% porosity, however, because their yield and ultimate compressive strength were smaller than anticipated, 5 more samples were tested to understand why the compressive strength were small. Additionally, two samples were lost because they were tested on a machine with a small load capacity. Figure 10 shows how the samples looked after testing was stopped. The aluminum foam was compressed significantly but did not crumble like the 10 PPI samples.

Like with the 10 PPI-cement paste samples, there is a slight bump in all of the lines, before the stress shoots up exponentially, indicating the yield stress of the samples. This is seen from strain values 0.03 to 0.07. The yield compressive strength of the 20 PPI-cement paste samples averaged out to be 778 psi (5.43 MPa), with the highest being 1766 psi (12.2 MPa) and the lowest 501 psi (3.45 MPa). At the yield point, the samples performed much worse compression than anticipated. The reason as to why is very uncertain.

Additionally, like with the 10 PPI-cement paste samples, the maximum compressive strength of the samples was determined by finding the maximum value in the plot where the stress begins to plateau (see Figure 9). This area was between the 0.10 to 0.30 strain range. The average maximum compressive strength of the samples was 1238 psi (8.53 MPa) (Table 2). The values ranged from 1610 psi (11.1 MPa) to 947 psi (6.53 MPa). The average ultimate compressive strength of the samples until the test stopped was 31,090 psi (214.3 MPa). The highest ultimate compressive strength was 42,442 psi (292.6 MPa) and the lowest was 19,359 psi (133.5 MPa).

The aluminum foam occupied 10.8% of the volume of the whole aluminum-cement paste sample. Using volume fractions, the theoretical compressive strength of this aluminum-cement paste composite should be about 2983 psi (20.6 MPa). The actual compressive strength was about 1238 psi (8.53 MPa), meaning there was a 73.6% decrease in yield behavior and 169% decrease in maximum strength. It is known that the compressive stresses of the composite sample will drop as porosity increases. However, given the results for the 40 PPI-cement paste samples, the reason for the drastic drop in yield for these samples remains unknown.

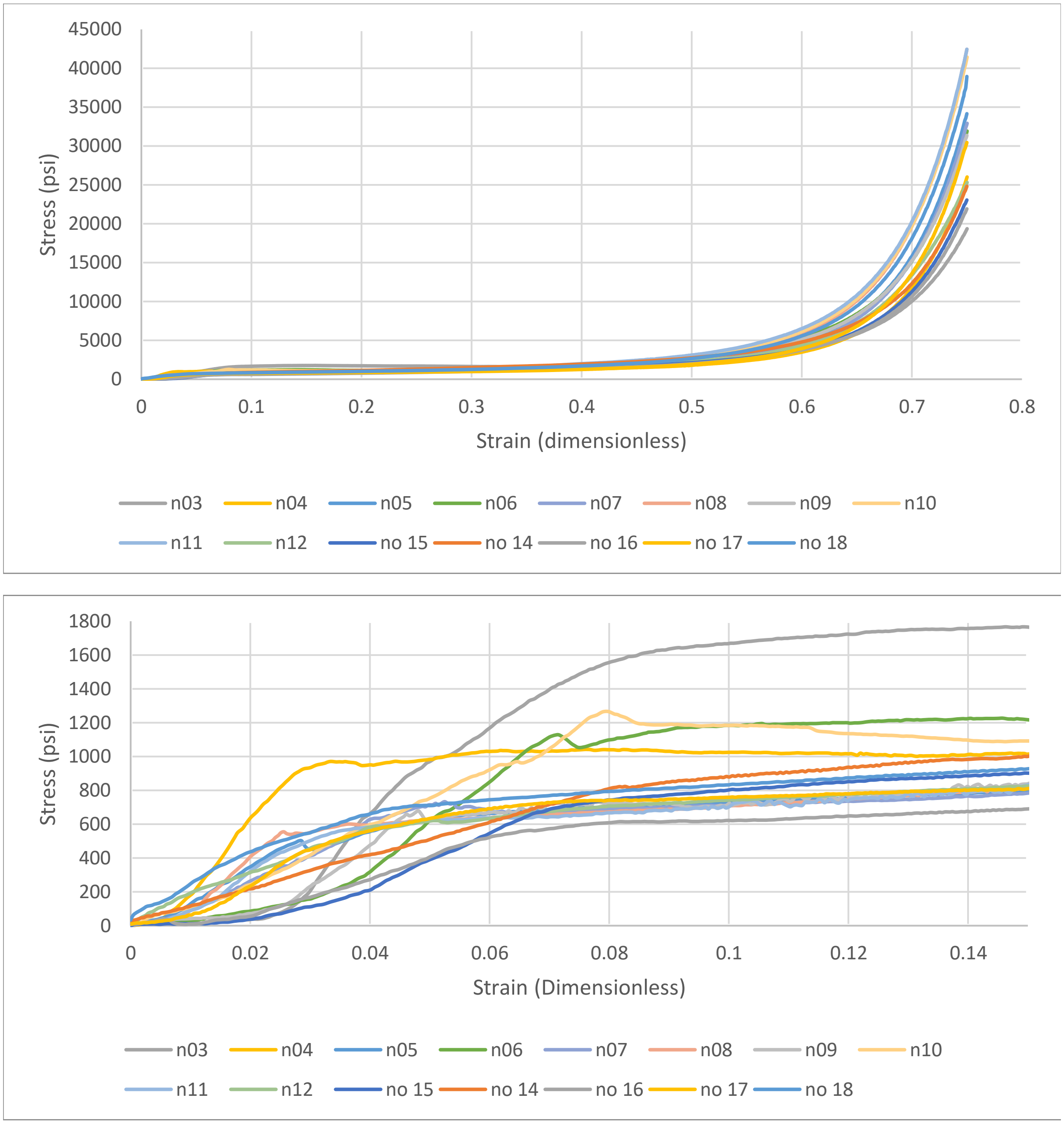


Figure 9. Stress vs. Strain plot of 20 PPI-cement paste samples.

Figure 10. “Failure” of the 20 PPI-cement paste samples.

4.4 40 PPI Foam-Cement Paste Samples

Figure 11 shows the stress vs. strain plot for the 40 PPI-cement paste samples tested in compression. It can be observed from the stress-strain curve that the yield point exists at a strain of roughly 0.05. Upon zooming into the graph at this yield point, it can be estimated that the samples have an average yield strength of 1885.4 psi (13 MPa), with the range for the samples ranging from 900 psi to 1400 psi (6.20 MPa to 9.65 MPa) just before a strain of 0.05.

Like with the other foam samples, the maximum compressive strength of the samples was determined by finding the maximum value in the area of the plot where the stress begins to plateau (see Figure 11). This area was between the 0.15 to 0.30 strain range. The average maximum compressive strength of the samples was 1156 psi (7.97 MPa) (Table 2) and the values ranged from 1388 (9.56 MPa) to 811 psi (5.59 MPa). The average ultimate compressive strength of the samples until the test stopped was 33,932.2 psi (233.9 MPa). The highest ultimate compressive strength was 48,142 psi (331.9 MPa) and the lowest was 25,702 psi (177.2 MPa). Figure 12 shows how the samples looked after testing was completed. The aluminum foam was compressed and crumbled similarly to the 10 PPI-cement paste samples.

The aluminum foam occupied 11.3% of the volume of the whole aluminum-cement paste sample. Using volume fractions, the theoretical compressive strength of this aluminum-cement paste composite should be about 2968 psi (20.5 MPa). The actual compressive strength was about 1156 ksi (7.97 MPa). These composites were 57% weaker yield in strength than the control and 10 PPI-cement paste samples. This measurement of yield strength is noticeably less than the range observed during the compression testing of the 10 PPI-cement paste samples and the control samples, further proving the hypothesis that the fewer pores per inch in the metallic foams used in the composite, the greater the yield strength of the composite.

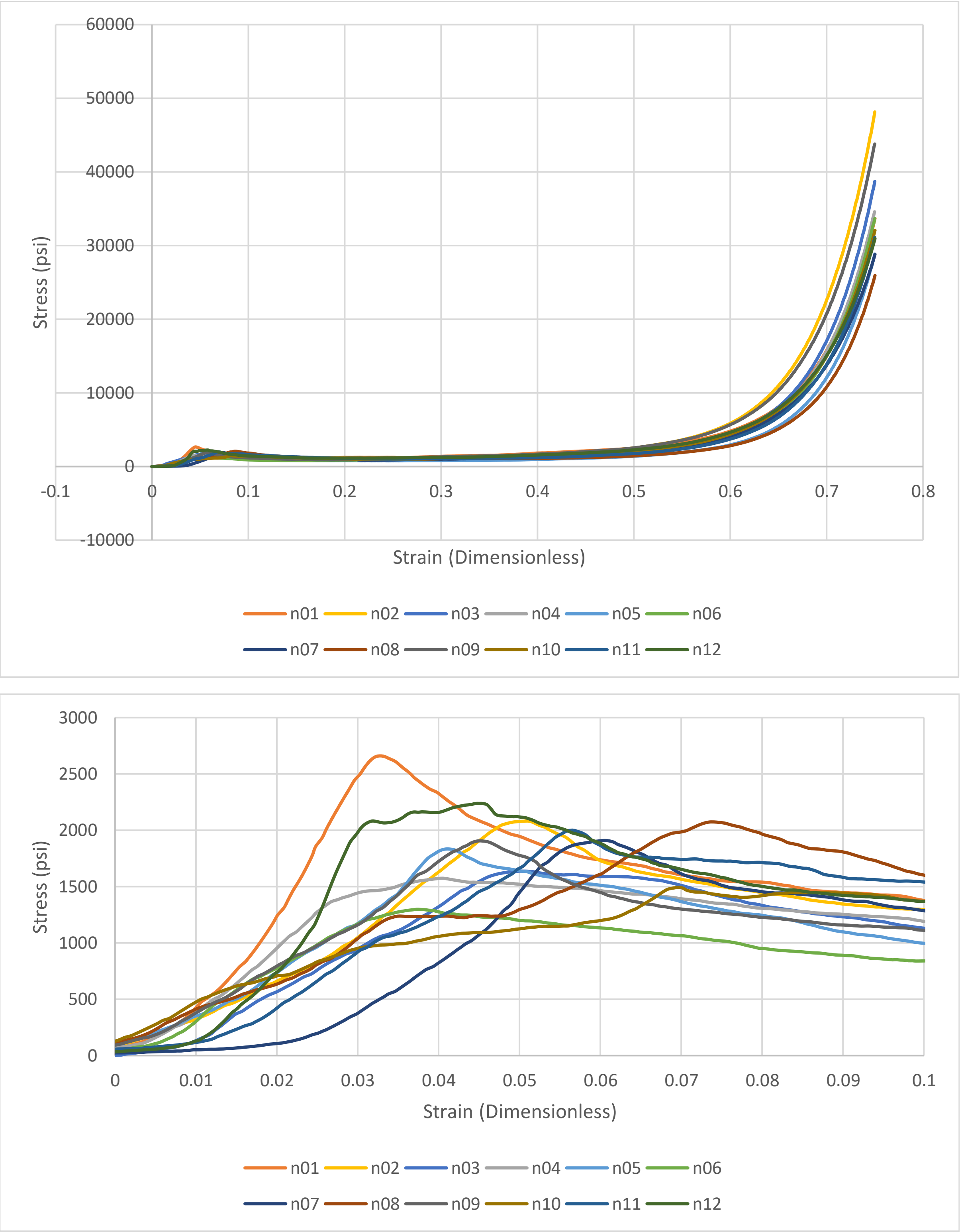


Figure 11. Stress vs. Strain plots of 40 PPI samples

Figure 12. "Failure" of the 40 PPI samples

4.5 Steel Fibers Reinforced Cement Paste Samples

The steel fiber samples were cast on December 7, 2020. They were tested using the same method as the control samples by PhD student Shuai Wang on December 21, 2020.

As shown below in Figure 13, the samples ultimately failed with cracking occurring from top to bottom, unsurprisingly indicating the stress of the vertical compressing force; the samples has similar columnar cracking like the control samples. The steel fiber reinforced composites – unlike their metallic foam counterparts – had less of a patterned distribution within the samples, and instead relied on the asymmetrical, scattered bunches of fibers to disrupt any internal fractures within the sample.

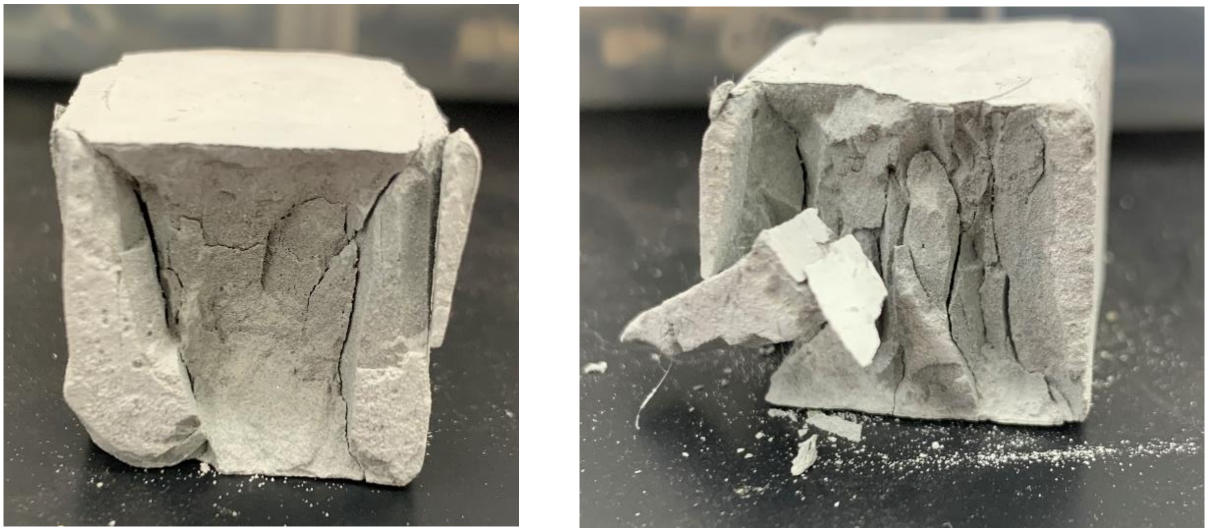


Figure 13. Failure images of steel fiber samples

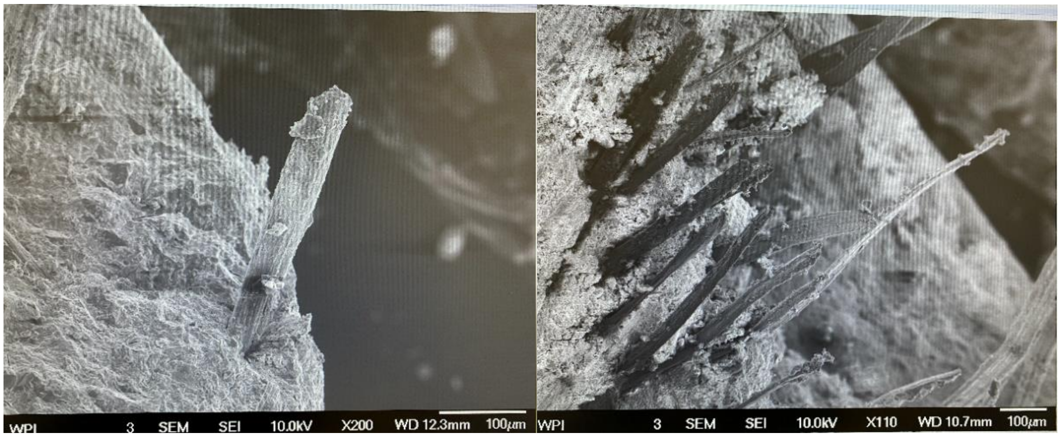


Figure 14. SEM images of steel fiber samples

Displayed in Figure 14 are the images taken of the steel fibers in their composites using a Scanning Electron Microscope (SEM). As seen both prior to testing and in the SEM images above, the steel fibers are not rigid or straight, despite being derived from a ferrous metal. Instead, the fibers rely on their greater material strength coupled with the rigid and stabilizing nature of the concrete around them to produce a superior composite. The results of the compression testing of the twelve steel fiber samples is shown below in Figure 15.

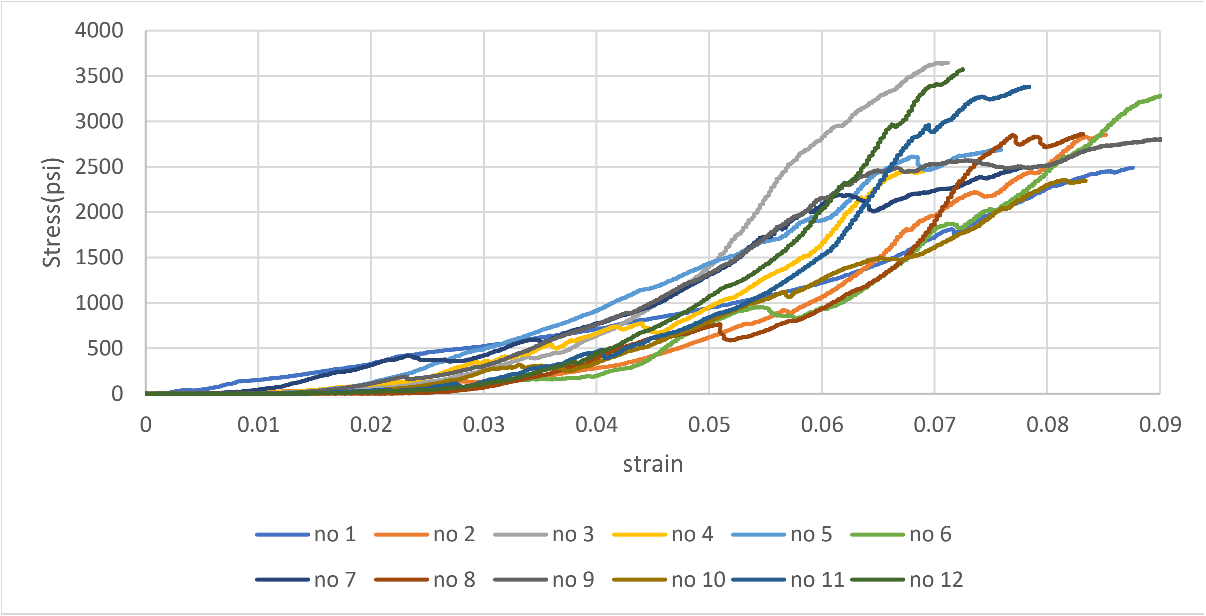


Figure 15. Stress vs. Strain plot of steel fiber samples

Of all the composite samples tested, the steel fiber samples had by far the most gradual stress-strain curve and an average ultimate stress of around 2909.17 ksi (20 MPa). The average ultimate compressive strength of the steel fiber composite samples above the yield stress of the 20 and 40 PPI foam-cement paste samples, but below the 10 PPI foam-cement paste and control samples.

4.6 Comparison of Reinforcement Methods

It was expected that the 10 PPI aluminum foam-cement paste composite would display greater compressive strength than the 20 PPI aluminum foam-cement paste composites, which would display greater strengths than the 40 PPI aluminum foam-cement paste composite, which in turn would, in theory, display greater compressive strength than the concrete control samples. Considering the mechanical behaviors and results displayed by the compression testing of the foam-cement paste composites, a decrease in the porosity of metallic foams supporting a concrete structure will result in an increase in the structure’s ultimate strength.

It was hypothesized – though not heavily anticipated – that the steel fiber composites would exhibit a higher tensile strength, as well as a higher modulus of elasticity, based on what is known of the material properties of steel fibers. These samples were additionally expected to outperform the concrete control samples in strength and produce results that indicated a composite material with superior mechanical properties than traditional reinforced concrete. These metal fiber composites were not expected to outperform the metallic foams, however, there most-likely exists a porosity-to-fiber threshold where the strength of the metal fiber composites is superior to metallic foams; such was not expected to be observed in our research.

Nonetheless, the same proof of concept stands for composites made of either metallic foams or metal fibers. Both composites were engineered to combine the structural properties of both materials and produce a composite with exponentially superior properties relevant to its intended usage, in our case, compressive and yield strength. From our results and the material properties of the components used, we can conclude that by combining aluminum foams of varying porosities with traditional concrete with a 0.5 water to cement ratio, a composite can be produced that exhibits a yield strength significantly superior to that of traditional reinforced concrete. Furthermore, yielding greater compressive strength than the material properties of either foam or concrete components would naturally produce. This implies that the structural design of the composite provides an additional advantage to the material properties of the composite. These design applications could span beyond reinforced concrete, and future research should be conducted on alternative material components to be used within concrete composites, that serve as a cheaper reinforcement without sacrificing compression strength.

While the metallic foam composite samples provided varying results in terms of strengths compared to one another in porosity, the steel fiber samples were less variable. These samples also did not have any alternative designs. As such, the conclusions drawn from the steel fibers were much straighter forward, compared to the metallic foam composite testing. Overall, the steel fibers when mixed with the concrete created a composite which displayed a product which was more malleable and flexible than traditional concrete and had an ultimate strength which was comparable to that of the best performing subset of the metallic foam composites (10 PPI) in terms of yield strength.

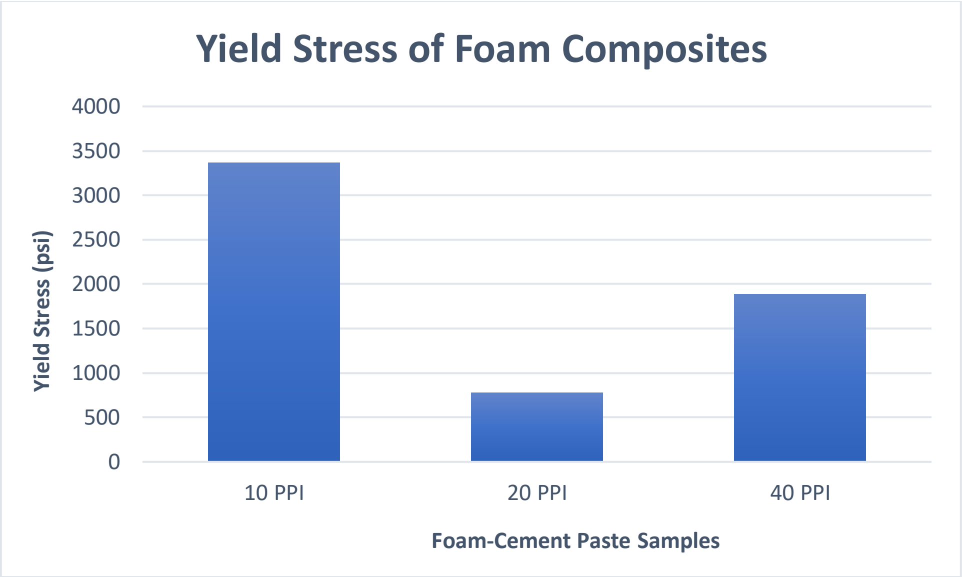


Figure 16. Yield Stress of Foam-Cement Paste Samples

The above plot displays the proportions of strength at the yield point between the three metallic foam composites. This would suggest a cheaper product than the metallic foam samples that could still offer a yield strength competitive with that of the 10 PPI-cement paste composites. The current results make a convincing case for an alternative material with a competitive yield strength, and low demand for metallic raw materials. This is especially important if economics plays a factor in reinforced concrete procurement.

5. ALUMINUM FOAM REINFORCED CEMENT PASTE COMPOSITE IN BUILDING DESIGN

A simply loaded three story building was designed in order to evaluate the capabilities of aluminum foam as reinforcement in concrete members. Figure 16 shows the building created in Risa 3D. The loads acting on the building are a 0.36 k/ft distributed live load along the beams on each floor, and a factored load of 159 kips. Analyzing a column that connects from the first floor down to the fixed support, the axial load acting on the column was 86 kips. Calculations were conducted on an 8” x 8” column that was reinforced with 10 PPI aluminum foam (since this was test group that the highest ultimate compressive strength out of all the foam porosities) and one that was traditionally reinforced with steel.

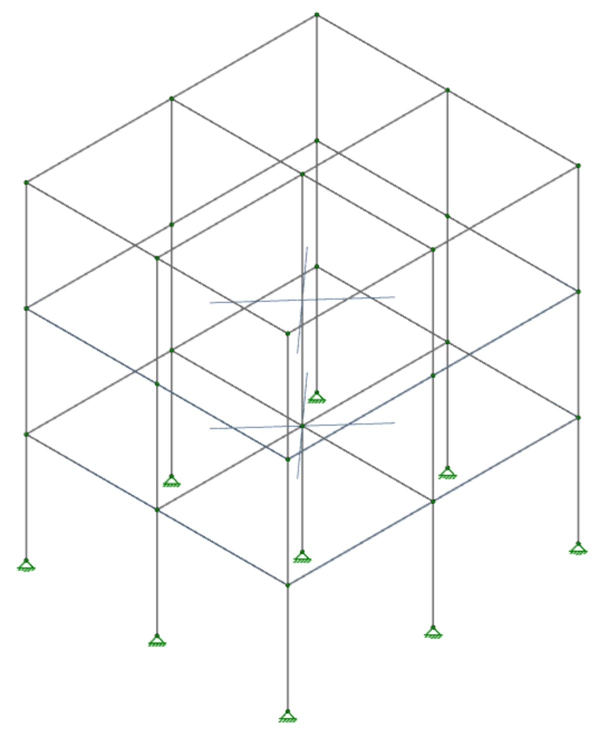


Figure 17. Risa 3D model of three-story building.

The volume of 10 PPI aluminum foam occupying a 1” cube of aluminum-concrete composite was 1.3549 cm^2 (0.209 in^2). Using the volume formula for a cube, the length of the foam was 1.1069 cm (0.435 in). Using that length, the surface area of the foam was found to be 7.3467 cm^2 (1.1387 in^2). This means that there was 1.1387 in^2 of aluminum foam per a 1” cube. Using proportions, it was found that for an 8” x 8”, with area of 64 in^2, the amount of aluminum foam required is 12.14 in^2. The stress in the concrete was calculated to be 970 psi (0.97 ksi). The axial load carried by the foam is 35344.4 lb. (35.4 kips). This means that 41% of the load that the column is subject to is carried by the aluminum reinforcement. The nominal axial strength for this column with 10PPI aluminum foam reinforcement is 414.8 kips and the axial design capacity is 270 kips. This indicates that the foam reinforcement allows for the column to withstand about three times more force than it is currently subjected to. Calculations conducted can be found in Appendix C.

To compare to steel reinforced concrete, the area of steel required for an 8” x 8” was calculated using the Risa 3D software and found to be 1.76 in^2. 4 #6 bars were used for the calculations of this design. Using the same axial load of 86 kips, the stress in the concrete was calculated to be 1123 psi (1.123 ksi) and the axial load carried by the steel is 15811.84 lb. (15.8 kips). 18% of the load is carried by the steel reinforcement. The nominal axial strength for this column with steel bar reinforcement is 232.6 kips and the axial design capacity is 151.2 kips. This indicates that the steel reinforcement allows for the column to withstand a little less than twice the force than it is currently subjected to. Calculations conducted can be found in Appendix D.

The concrete undergoes far more stress when reinforced with steel than it does when reinforced with aluminum foam. The foam reinforcement is also able to carry more of the load than the steel, which can be attributed to the fact that the foam is required to have more area within the column than the steel. Because the foam occupies more space within the column, it can take some of the stress due to the load away from the concrete and carry it within itself. Based on these calculations, in theory, the foam could be used as reinforcement in a structural element that requires higher ductility and toughness in compression.

This analysis shows the potential in the real-world application of the composite materials researched, as the metallic foams have been shown to provide significant augmentation when substituted into existing structures, allowing for a significantly greater load, thanks to its considerably high ultimate strength (seen in Figure 7) and a considerable yield strength, which is similar to that of typical normal weight concrete. In many situations where the length, width, or volume of supporting members in structural engineering of a design is a limiting factor, the alternative foam reinforced composites explored here could be used as a substitute or augmenting material for the purpose of limiting dimensions or supporting considerable loads.

6. CONCLUSION

The purpose of this project was to evaluate the feasibility of replacing rebar with metallic foams and fibers as reinforcement for concrete. Five testing groups were subjected to compression testing: A control concrete group, 10 PPI aluminum foams, 20 PPI aluminum foams, 40 PPI aluminum foams, and steel fibers.

The 10 PPI aluminum foam when mixed with cement paste produced a foam-cement paste composite with a similar yield compressive strength to that of the maximum strength of the control samples. Compared with to the control samples, the 10 PPI foam-cement paste samples increased the yield strength of the foam composite by 14% but had a decreased maximum compressive strength by 30%. The 20 PPI foam-cement paste samples had a much lower yield and maximum strength than expected, decreasing in maximum compressive strength by nearly half. The 40 PPI foam-cement paste had a smaller yield and ultimate strength as anticipated with the maximum strength being similar to the 20 PPI composites and decreasing the yield by nearly the same amount. Nonetheless, the foam-cement paste samples were able to ultimately withstand a much higher compressive stress than the control samples could.

Because of the plastic behavior of the aluminum foams, these composite samples were able to withstand higher stresses than typical control samples or reinforced concrete. Beyond the foam samples, the steel fiber composites produced an average ultimate stress that was less than the ultimate strength of the control samples but was still better than the yield stresses of the 20 and 40 PPI foam-cement paste samples. Out of the reinforcement concrete composites examined, the 10 PPI aluminum foam proved to be the best reinforcement option.

To test its real-world applications, the 10 PPI aluminum foam-cement paste composites were simulated in a sample design of a three-story building. The usage of this material in an 8” x 8” column yielded results that – when compared with the amount of rebar necessary for the same sized column – the aluminum foam reinforcement was able to support a greater load and had double the nominal axial strength.

Based on these discoveries of the favorable strengths of concrete composites with 10 PPI, 20 PPI, and 40 PPI aluminum foams, and steel fibers, further research is encouraged to determine the ideal porosity when using metallic foams as a reinforcing material for different concrete applications. Fibers can also be further explored using different metals, varying concentrations, and even specific orientations within the design. In summary, the results of the material testing have been promising to the potential feats of strength in these composite materials, and further research is worthwhile to explore the optimization of existing and alternative designs to the structures created during this project. It is the expectation that this concept when optimized could provide a superior alternative to reinforced concrete and allow for real-world applications throughout the field of civil and structural engineering.

REFERENCES

AZoM. (2002, June 4). Aluminum – Advantages and Properties of Aluminum. *AZO Materials*. https://www.azom.com/article.aspx?ArticleID=1446.

Bao F., Davidson J. (2015). Analysis of partially composite foam insulated concrete sandwich structures. *Engineering Structures* 91, 197-209. https://doi.org/10.1016/j.engstruct.2015.02.033.

Dante, Roberto C. (2016) 9 - Metals, Handbook of Friction Materials and their Applications, Woodhead Publishing, Pages 123-134, ISBN 9780081006191, https://doi.org/10.1016/B978-0-08-100619-1.00009-2.

Davis, J. R. (1999). *Corrosion of Aluminum and Aluminum Alloys*. ASM International. ISBN 978-1-61503-238-9.

Eltayeb E., Ma X., Zhuge Y., Youssf O., Mills J.E., Xiao J. (2020). Structural behaviour of composite panels made of profiled steel sheets and foam rubberised concrete under monotonic and cyclic shearing loads. *Thin-Walled Structures* 151, 106726. https://doi.org/10.1016/j.tws.2020.106726.

García-Moreno F. (2016). Commercial Applications of Metal Foams: Their Properties and Production. Materials (Basel, Switzerland), 9(2), 85. https://doi.org/10.3390/ma9020085

Küster K., Barburski M., Lomov S., Vanclooster K. Chapter 10 - Metal Fibers—Steel, Editor(s): Boris Mahltig, Yordan Kyosev. (2018). In The Textile Institute Book Series, Inorganic and Composite Fibers, Woodhead Publishing, Pages 219-241, ISBN 9780081022283, https://doi.org/10.1016/B978-0-08-102228-3.00010-4.

McCartney D. (2016, July 17). The problem with reinforced concrete. *The Conversation*. https://theconversation.com/the-problem-with-reinforced-concrete-56078.

National Ready Mixed Concrete Association (NRMCA). (n.d.). CIP 35. Testing Compressive Strength of Concrete. https://centralconcrete.com/wp-content/themes/centralconcrete/images/cip/35pr.pdf.

National Society of Professional Engineers (NSPE). (n.d.) What is a PE?. *NSPE*. https://www.nspe.org/resources/licensure/what-pe#:~:text=To%20become%20licensed%2C%20engineers%20must,from%20their%20state's%20licensure%20board.&text=To%20use%20the%20PE%20seal,steps%20to%20ensure%20their%20competency.

Prahba P., Palani G. S., Lakshmanan N., Senthil R. (2017). Behaviour of steel-foam concrete composite panel under in-plane lateral load. *Journal of Constructional Steel Research* 139, 437-448. https://doi.org/10.1016/j.jcsr.2017.10.002.

Rammurty U., Paul A. (2004). Variability in mechanical properties of a metal foam. *Acta Materialia* 52 (4), 869-876. https://doi.org/10.1016/j.actamat.2003.10.021.

Ranut P., Nobile E., Mancini L. (2014). High resolution microtomography-based CFD simulation of flow and heat transfer in aluminum metal foams, Applied Thermal Engineering, Volume 69, Issues 1–2, 2014, Pages 230-240, ISSN 1359-4311, https://doi.org/10.1016/j.applthermaleng.2013.11.056.

Rodriguez, J. (2019, August 16). Uses and Applications for Steel Fiber Concrete. Retrieved October 14, 2020, from https://www.thebalancesmb.com/what-is-steel-fiber-concrete-uses-and-applications-844458.

Słowik, M. (2019). The analysis of failure in concrete and reinforced concrete beams with different reinforcement ratio. *Arch Appl Mech* 89**,** 885–895. https://doi.org/10.1007/s00419-018-1476-5.

Statista Research Department. (2020, February 13). U.S. and world cement production 2019. *Statista.* https://www.statista.com/statistics/219343/cement-production-worldwide/ .

Vale B. (2017). Building materials. *Materials for a Healthy, Ecological and Sustainable Built Environment: Principles for Evaluation* (pp. 67-122). Woodhead Publishing. http://dx.doi.org/10.1016/B978-0-08-100707-5.00003-4.

Van Zijl G., Van Rooyen A.S. (2018). Developing Reinforced Foam Concrete as a Composite Material for Durable Structural Application. *4th Brazilian Conference on Composite Materials.* DOI: 10.21452/bccm4.2018.02.22.

APPENDIX

Appendix A: Tables of Maximum Compressive Strength of Test Samples

Table A1. Maximum Compressive Strength of Control Samples

Sample #	Max. Comp. Strength (psi)
1	2446.1
2	3437.3
3	2879.6
4	2354
5	3323.9
6	3854.8
7	3770.7
8	3344.2
9	2702.4
10	4126.1
11	3026.5
12	3010.5
13	3987.4
14	4368.8
15	3589.5

Table A2. Maximum Compressive Strength of 10 PPI Foam-Cement Paste Samples

Sample #	Max. Comp. Strength (psi)
1	2638
2	2666
3	3352
4	2572
5	2474
6	2712
7	3069
8	2240
9	2252
10	2356
11	2360
12	2129

Table A3. Maximum Compressive Strength of 20 PPI Foam-Cement Paste Samples

Sample #	Max. Comp. Strength (psi)
1	n/a
2	n/a
3	1670
4	1220
5	1123
6	1345
7	1054
8	1306
9	1208
10	1282
11	1330
12	1072
13	1218
14	1494
15	1006
16	987
17	1260

Table A4. Maximum Compressive Strength of 40 PPI Foam-Cement Paste Samples

Sample #	Max. Comp. Strength (psi)
1	1388
2	1247
3	1012
4	1093
5	811
6	1099
7	997
8	1227
9	1311
10	1193
11	1253
12	1239

Table A5. Maximum Compressive Strength of Steel Fiber Samples

Sample #	Max. Comp. Strength (psi)
1	2490
2	2856

3	3646
4	2469
5	2690
6	3284
7	2486
8	2861
9	2821
10	2348
11	3383
12	3576

Appendix B: Yield Compressive Strengths of Aluminum Foam-Cement Paste Samples

Table B1. Yield Compressive Strength of 10 PPI Foam-Cement Paste Samples

Sample #	Max. Comp. Strength (psi)
1	3955
2	3070
3	3807
4	3233
5	3109
6	3301
7	4247
8	3012
9	2746
10	3624
11	3308
12	2974

Table B2. Yield Compressive Strength of 20 PPI Foam-Cement Paste Samples

Sample #	Max. Comp. Strength (psi)
1	n/a
2	n/a
3	1266
4	1128
5	616
6	549
7	501
8	676
9	820
10	1766

11	970
12	555
13	710
14	724
15	620
16	740
17	737

Table B3. Yield Compressive Strength of 40 PPI Foam-Cement Paste Samples

Sample #	Max. Comp. Strength (psi)
1	2655
2	2082
3	1637
4	1537
5	1834
6	1294
7	1909
8	2074
9	1906
10	1448
11	2000
12	2238

Appendix C: Design Calculations for Aluminum Foam Reinforced Beam

Volume of 10 PPI Aluminum Foam in 1" Aluminum-Concrete Composite sample

$m = 3.6583\,g$ (avg amongst 12 sample)

$d = 2.7\,g/cm^3$

$V = \frac{m}{d} = \frac{3.6583\,g}{2.7\,g/cm^3} = 1.3549\,cm^3$

$V = s^3$

$1.3549\,cm^3 = s^3$

$\therefore\ s = 1.1066\,cm$

Area of Aluminum Foam occupied in 1" sample

$A = 6s^2 = 6(1.1066\,cm)^2$

$A = 7.3467\,cm^2 = 1.1387\,in^2$

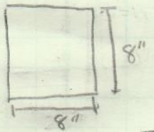
$\therefore$ 1.1387 in^2 of aluminum foam per 1" ($6\,in^2$) sample

using proportions:

$\frac{1.1387\,in^2}{6\,in^2} = \frac{x}{64\,in^2} \quad \therefore\ x = 12.14\,in^2$

Based on these calculations, the required area of aluminum reinforcement for an 8"x 8" column is 12.14 in^2

Column reinforced with aluminum foam



$f'c = 3500$ psi $\quad fy = 30$ ksi $\quad Pu = 85.697^k$

$Aa = 12.14\,in^2 \quad E = 9800$ KSI

$Ag = 51.86\,in^2$

$fr = 7.5\sqrt{f'c} = 7.5\sqrt{3500} = \underline{443.71}$ psi

$Ec = 57000\sqrt{f'c} = 57000\sqrt{3500} = 3372165$ psi $= 3372$ Ksi

$n = \frac{Es}{Ec} = \frac{9800\,ksi}{3372\,ksi} = 3$

$Pu = fc\,(Ag + nAa)$

$85.697^k = fc\,(51.86\,in^2 + 3(12.14\,in^2))$

$fc = 0.97$ Ksi $= 970$ psi

$Ps = nfcAa = 3(970\,psi)(12.14\,in^2)$

$Ps = 35354.4$ lb $= 35.4$ kips

$Pn,max = 0.8\,(0.85f'c\,(Ag - Aa) + fy\,Aa)$

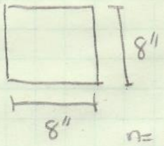
$= 0.8\,(0.85\,(3.5\,KSI)(51.86\,in^2) + (30\,KSI)(12.14\,in^2))$

$Pn,max = 414.786\,K$

$\Phi Pn,max = 0.65(414.8^k) = 269.6^k$

Appendix D: Design Calculations for Steel Reinforced Beam

column Typically Reinforced with Steel Bars



$f'_c = 3500$ psi $\quad f_y = 60$ KSI $\quad f_r = 443.7$ psi

$A_s = 1.76\ in^2 \quad E = 29000$ KSI $\quad E_c = 3372$ KSI

4 #6 $\quad A_g = 62.24\ in^2 \quad P_u = 85.697^k$

$$n = \frac{29000\ KSI}{3372\ KSI} = 8$$

$$85.697^k = f_c\,(62.24\ in^2 + 8(1.76\ in^2))$$

$$f_c = 1.123\ KSI = 1123\ psi$$

$$P_s = n f_c A_s = 8(1123\ psi)(1.76\ in^2)$$

$$P_s = 15811.84\ lb = 15.8\ ^{Kip}$$

$$P_{n,max} = 0.8\,(0.85\,(3.5\ KSI)(62.24\ in^2) + (60\ KSI)(1.76\ in^2))$$

$$P_{n,max} = 232.6\ K$$

$$\phi P_{n,max} = 0.65\,(232.6^K) = 151.2K$$