Lightweight Concrete:

Investigations into the Production of Natural Fiber Reinforcement

by

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Abstract

The purpose of this study is to investigate the benefits of adding natural fiber tensile reinforcement to aerated concrete. Concrete is a great composite material which can be created in various proportions and with various materials to alter its strength, density and porosity, amongst other properties. Concrete which is used commonly in construction of columns, beams, and slabs acts well in compression but fails under tension. The common solution is to reinforce the structure in areas where it experiences tension with steel. There are other materials besides steel which also take tension well. Natural fibers for example come in various strengths and types and would create lighter and perhaps more sustainable beam designs. Natural fibers have been used for their availability, workability, and high tensile strengths for centuries.

This research discovers how the natural fibers distribute within the mixture and how they affect the aeration of the concrete, as well as how they affect the strength. Multiple samples are cured with different fiber types and in different proportions within the mixture. Furthermore, similar experimentation is conducted to discover an ideal ratio of aggregate to aerated concrete mix. The aggregate gives the concrete greater strength and economy, but could negatively affect the aeration. The various concrete mixes are poured and allowed to cure to maximum strength before indirect tensile tests and compression tests are conducted. The effects of creating smooth aerated concrete molds are also investigated. All experiments conducted are precursory to an ultimate tensile reinforced aerated concrete beam design with an aggregate mix and smooth surfaces.

Thesis Supervisor: John Fernandez
Title: Associate Professor of Architecture and Building Technology and Engineering Systems

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1. Introduction

This introduction outlines the ideas brought together that culminated with the completion of this thesis. This thesis is a requirement for completion of the Degree of Bachelor of Science in Architecture degree with the Building Technology group.

Low-rise concrete construction, although not used much in the United States, is common in developing nations. In these parts of the world, often times, these homes are constructed without reinforcement due to economic constraints and material availability. In the October 2005 earthquake which struck the India-Pakistan border 74,000 people died and almost the same number were injured. Earthquake records indicate that 60% of earthquake deaths in the last century are due to the collapse of unreinforced concrete structures.[1] In such cases, natural fiber reinforcement is a feasible solution for designing earthquake resistant low-rise homes. Even preventing sudden collapse could help save many lives.

Sustainability has become a commonly discussed topic amongst the built environment. Building materials, especially concrete, have high embodied CO_2 and contribute annually to the CO_2 already in the atmosphere. Efforts have been made to make concrete a more sustainable material by using recycled materials in the composite mix, as well as reducing the amount of material needed in a structural member. This research has led to discoveries in lightweight concrete, a cellular composite using less material. Why not combine concrete research with sustainable natural fiber usage as reinforcement?

Yes, it is possible to reinforce lightweight aerated concrete with steel rebar or wire mesh, as is commonly done with normalweight concrete; however, using natural fiber reinforcement is less expensive and more sustainable. In certain locations, especially in developing nations, natural fibers are more available than steel which is transported from manufacturers, further increasing the embodied energy of the material.

There are examples all around the world, which show the inherent tensile strength of many natural fibers. In Peru, there are still villages that keep the ancient Inca tradition of rope bridges spanning over rivers and canyons (Figure 1). These bridges can hold many people and are made solely of woven grass[2]. Fiber weaving is a skill which many women possess in developing nations. An industry in this material would increase work opportunities for woman and shift the social norms for these regions where there is currently little work available for women.

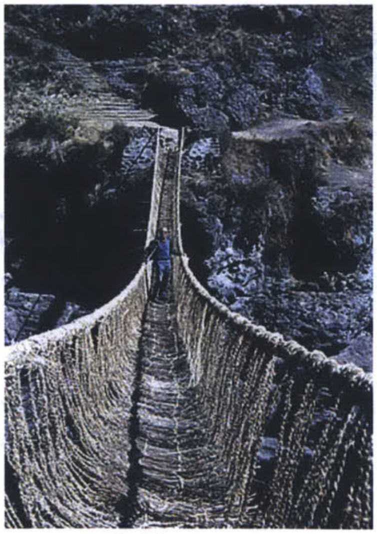

Figure 1: Inca rope bridge[3]

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[1] (Coburn, 2002)

[2] (Kramme, 2012)

[3] (Ancient Rope Bridges, 2013)

This research works towards developing a fully functional aerated concrete. Results from this research can be used as stepping stones in the formation of a lightweight aerated concrete with a competitive strength, while simultaneously using sustainable materials and less material overall.

1.1 The Motivation

I stumbled upon an exhibit on lightweight concrete at the Massachusetts Institute of Technology. There, I saw the research of Timothy Graham Cooke, a graduate student at the Massachusetts Institute of Technology, who was finishing his thesis titled "Lightweight Concrete: Investigations into the production of variable density cellular materials" for his Master of Science in Architecture Studies. The exhibit displayed various concrete molds made with non-autoclaved aerated concrete (Figure 2). Many of these samples had been cured in varying conditions, using different methods, in an effort to see the effects on the variable density throughout the sections.

Figure 2: Exhibit on variable density concrete[4]

Cooke's particular research with lightweight concrete and its use in structural beams fascinated me and I quickly began thinking about how to further the research. The beams took advantage of the variable density caused by simple gravity curing to provide compressive strength where it was necessary in the beam, while using less material where it was not needed (Figure 3). The question of tensile reinforcement floated around in my mind; until I had the pleasure of meeting Cooke and discussing ways in which I could take his investigations and focus them on creating stronger structural beams with tensile reinforcement.

Figure 3: Varying density in a beam cast[5]

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[4] Photo Credit: Timothy Cooke

[5] Photo Credit: Timothy Cooke

1.2 Research Overview

The most productive way to learn about concrete and its behavior in relation to other factors such as fibers, aggregates and smooth surfacing, is to be hands-on with the material. This thesis takes a 'get your hands dirty' approach to researching lightweight concrete.

Each experiment develops from the results and observations of previous experiments. When a "what would happen if..." or "what if..." question developed, an experiment was immediately outlined to help answer it. The hardest part in developing the research was the overall time constraint, since the Type I/II Portland Cement used in the concrete mixes require weeks to cure and will not reach maximum strength for months. In most individual topics studied, many more experiments could be conducted and many more samples could be made.

Understanding the uses, origins, and basics of normalweight concrete, was important in asking the right questions and driving experiments in a direction which would ultimately yield useful results. Chapter 2 dives into the necessary background related to normalweight concrete and practices currently used in industry. Existing methods of forming aerated concrete and its uses are also explored.

1.3 Thesis Outline

Chapter 2 gives background on relevant basics of concrete construction and fiber reinforced concrete. It elaborates on the idea of reinforcing concrete with fibers and discusses the benefits with regard to sustainability and strength.

Chapter 3 consists of a series of experiments outlining motivation and strategy, as well as, qualitative and quantitative results. Natural and synthetic fiber strands are observed and tested for homogeneity and workability. These same strands are cut and added to aerated concrete in different doses to observe effects on the aeration process. Fiber distribution throughout the mold is also noted. Saturated and unsaturated fiber rope is inserted into molds, representing steel rebar reinforcement. Aggregates are added to knowledge from previous experiments to form a better concrete. The surface of molds is removed at different points in the process to develop an ideal time frame for smoothing the top of molds.

Chapter 4 provides a summary of the work. It highlights individual results from singular experiments and analyzes them alongside structural background knowledge. Conclusions are reached using the various analyses and future work is outlined. Supporting graphs, experimental data, and images are provided in Appendix A and Appendix B.

2. Background

This section presents a context in which the research is situated. A brief history of concrete is presented and its use as a material currently amongst the built environment. The common components of normalweight concrete are defined, as well as variations relevant to the investigations in this thesis. This includes developments in lightweight and aerated concrete and their uses, as well as the differences between existing types of aerated concrete and the methods used to form them. Fiber reinforcement is examined with regards to natural and synthetic fibers.

2.1 Concrete

In the built environment, developments in reinforced concrete have proven it to be a leading material resistant to natural disasters and impact. It is inherently durable and low cost with respect to maintenance, due to its ability to resist water, moisture, rot, rust, temperature changes, and fire. Additionally, the strength of concrete has significantly increased in recent years, making it competitive in the market. High-strength concrete, with a strength of 100MPa is being used for high-rise building columns.[6] The United States is known for an abundance of wood; which made it the leading material in low-rise construction for centuries. As the abundance of large trees dwindles, concrete becomes a feasible option for low-rise construction.[7] Concrete also offers designers the ability to imagine and create an endless possibility of shapes and finishes. With these innovations concrete curves are easier to construct and the addition of different materials changes the color and finish.

Origins

Concrete structures date back to the Ancient Romans and the construction of the Pantheon and Coliseum. Experimenting with the effects of additives in concrete also dates back to the time of the Romans. They discovered that using ash from volcanoes as the mortar in combination with sand, gravel and water, allowed the concrete to set underwater. Proactively, they added horsehair into the mix to restrain cracking during hardening. They also discovered that adding animal blood into the mixture created air bubbles which made the concrete more resistant to frost and reduced thermal effects.[8] The process for making concrete was lost with the downfall of the Roman Empire; however the art was rediscovered around the mid-18th century.

Basics

Concrete is a composite material; generally composed of cement, aggregates and water. There are many variations with additives that adjust strength, durability, thermal properties, and workability based on desired use.

Aggregates increase the durability of the otherwise brittle cement and usually compose the majority of the mixture. The use of aggregates also reduces the cost of the mixture as they are less expensive than pure cement. Aggregate size is based on the largest pieces of aggregate in the mix. Fine aggregates, such as sand and finely crushed stone, serve as filler. Coarse aggregates, such as coarse gravel or crushed rocks, serve to increase the strength of the concrete.

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[6] (Ho, 2012)

[7] (VanderWerf, Panushev, Nicholson, & Kokonowski, 2006)

[8] (Aïtcin, September 2000)

Cement serves as the binder for the aggregate and other materials. Commonly used cement is Portland Cement which comes in several types, the most frequently used are I, II, and III.

- **Type I** is a general purpose cement and is usually assumed to be used unless otherwise stated.
- **Type II** is used for general construction which could be exposed to soils and ground water, since it is more resistant to shrinkage; however it gains strength slowly.
- **Type III** is used when high early strength is required. The seven day compressive strength is comparable to the 28 day strength of Type I/II; however long term strength is compromised. [9]

Water initializes an exothermic chemical reaction with the cement which allows for the binding of the mixture, while releasing heat. The percentage of water added to the dry mix affects the workability of the mixture as well as the potential for the cement to reach maximum strength. Cement can cure with a water-cement ratio (w/c) of 0.28 or higher but is difficult to work at a low w/c. In most uses in the construction field a w/c of 0.4-0.5 is designed. Ratios higher than 0.5, begin to weaken the strength of the material.[10]

Air-entrainers create air bubbles in the concrete which increase durability with respect to thermal capabilities and frost resistance. When a mix contains a large percentage of air bubbles, the air-entrainers help create a lightweight material.

Reinforcement

Concrete is a brittle material and weak in tension, therefore forming cracks easily. For these reasons, reinforcement is used to strengthen the durability of concrete. Reinforcing concrete is common practice and can be done in many different ways including steel rebar, wire mesh, fibers and foam. For the scope of this paper details on fiber reinforcement are presented.

- **Wood-fiber** reinforcement is used in cement to create a durable concrete which is significantly more flexible. This allows thin sections to flex or be connected with screws and nails without splitting. Wood chips are added into the concrete mix in place of coarse aggregates.
- **Fiber strand** reinforcement is traditionally used to control cracking; however when used in large quantities the fibers can substitute for the use of rebar by increasing structural strength. Strands of fibers are mixed into the concrete and the varying concentrations of fibers in the mix are commonly referred to as doses.

These fibers can be of steel, glass, synthetic or natural. Synthetic fibers refer to man-made materials such as steel polypropylene, glass and graphite fibers. Natural fibers refer to natural materials such as wood or sisal, hemp and jute fibers used for experiments in this research. Synthetic fibers are usually engineered to have a higher tensile strength than natural fibers; however natural fibers are more sustainable and economical.

The fibers are not meant to increase the compressive strength of concrete, although

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[9] (Portland Cement Association, 2013)

[10] (VanderWerf, Panushev, Nicholson, & Kokonowski, 2006)

sometimes small increases do occur. They are meant to provide post-cracking ductility. The effectiveness of the fiber reinforcement is dependent on the adherence of the fibers to the matrix structure of the concrete.[11] Occasionally, the fibers can be surface treated to increase the bond with the matrix, since smooth surface fibers are more susceptible to slipping. There are two primary methods of fiber failure, breaking and slippage. The latter, also referred to as fiber pull-out is preferred since greater energy is needed to remove the fibers from the matrix. Toughening of the composite occurs, when cracking begins to form in the matrix; however the various sections of the concrete are held together by the fibers. This increases the post-cracking ductility of the composite.

2.2 Lightweight Concrete

Lightweight concrete refers to concrete with a density less than 2400kg/m^3 which is that of the average normalweight concrete.[12] This can be made by using lighter aggregates, having a cellular structure, in the mixture. It also includes, lightweight cellular concrete which is made using air-entrainers to create air bubbles within the concrete matrix

Lightweight cellular concrete can be autoclaved or simply aerated. In a building, aerated concrete members can act simultaneously as the structural component, as well as insulation, mold resistance and fire proofing. Products created from aerated concrete range from wall panels to blocks, roof panels and floors.

Autoclaved aerated concrete (AAC), also known as autoclaved cellular concrete or autoclaved lightweight concrete, is produced by mixing cement with air-entrainers and curing it in an autoclave. Here, the mold is steamed under high temperatures and pressure keeping it moist, accelerating the curing process and controlling aeration.[13] Depending on its prospective use, AAC is produced in various densities and analogous compressive strengths.

Non-autoclaved aerated concrete is left to cure at room-temperature and under normal atmospheric pressures. The strength of the concrete develops slowly, however the embodied energy of the final product is significantly less considering there is no need for an autoclave.

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[11] (Mindess, Fibrous concrete reinforcement, 2008)

[12] (Bremner, 2008)

[13] (Cooke, 2012)

2.3 Sustainability

In the world, concrete is the second most consumed resource after water and it is the most consumed material, with a yearly consumption of almost nine times that of steel (Table 1). Due to the quantity in which it is consumed it contributes 5% of the annual anthropogenic CO_2 in the atmosphere.[14] Production of one tonne of cement, the main component of concrete, consequently results in the release of about one tonne of CO_2.[15] Making cement is a very energy intensive process and worldwide it is estimated that the cement industry is responsible for 7% of all CO_2 generated.[16] Additionally, the production of Portland cement requires large amounts of water which can be a problem in areas without access to abundant fresh water.

Table 1: Annual production of materials[17]

Material	*Annual production (billion tonnes)*
Concrete	8.7
Steel	1
Salt	0.2
Sugar	0.135
Oil	5.2

Lifecycle cost analyses and the embedded energy of concrete indicate that concrete is essentially an environmentally friendly material, however the Portland cement is what makes it harmful to the environment. Therefore, perhaps the Romans had the right idea with the use of recycled volcanic ash as a mortar.

Lightweight concrete using fly ash as a supplementary cementitious material is a step in the right direction in designing a more sustainable concrete; however tensile reinforcement must be taken into account. The fly ash is generated in combustion and comes from the remnants of coal burning. It is lighter than cement which reduces the overall weight of a structure therefore reducing the size of structural members. It helps to create a more sustainable composite material.

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[14] (Crow, March 2008)
[15] (Mindess, Introduction, 2008)
[16] (Malhotra, 2000)
[17] (Mindess, Introduction, 2008)

3. Investigations

This section presents various experiments that were conducted, documenting effects of various additives to a general aerated concrete mix. These investigations include the workability and distribution of cut fibers within the concrete mix, the effects of fiber rope in the mix and the addition of aggregate to the concrete mix. Motivation, procedures, and results are outlined for each test.

A general mix ratio (Table 2) for the aerated concrete is used throughout experiments unless otherwise stated. This mix has a 5 : 11 water to dry mix ratio. Early testing has been conducted to see how altering the water content affects aeration and workability. This mix was found to be easy to mix and to aerate well within a few hours of pouring. Experiments to follow add materials into the mix and observe effects on the workability, aeration, distribution, and strength.

Table 2: Proportions of general concrete mix used

Material	*Quantity (grams)*	*% of Total Dry Mass*
Water	750	--
PC Cement Type I/II	500	31
Fly Ash	1000	62
Quicklime	130	7
Aluminum Paste	2	0.12

For any experiment involving compression cylinders as molds, these are all 4 inch diameter and 8 inch tall cylinders, unless otherwise stated. Cylinder molds were used to allow for a large quantity of molds to be poured simultaneously. Using the compression cylinders for all experiments gives the option of compression testing and indirect tension testing as per ASTM C39 *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.*[18] In many cases multiple cylinders were poured per mix, both for consistency and to allow for different testing and observing later.

3.1 Fibers and Water

Natural fibers are natural, meaning they come in tangled strands and often times with other particulates distributed in the mix and attached to strands of fiber. Some fibers are cleaner than others by the nature of their composition. Sisal fibers are monochromatic and smoother, whereas jute is rough and strands vary in thickness and color. In this experiment, sisal, hemp, and pulled jute of qualities 1 and 2 were used. Understanding the workability of these fibers was important in devising a way of ultimately adding them to a concrete mix.

The intention was to grasp an understanding of how easy or difficult it is to clean and chop the fibers. It was just as important to test how well the fibers mix with the water. Do they distribute throughout the mixing container? Are they hydrophobic and therefore clump together? Is there some other distribution?

The Strategy

A handful of each natural fiber type was run under cold water in a sink to preliminarily remove particulates before the fibers were cut. Compressed to 50ml dry volume, each fiber type was then cut by hand using scissors to lengths between a quarter inch and a half inch.

After being cut, these fibers were added to 500ml of water, where they were again rinsed and in most cases any debris left floated to the top where it could be scooped out. The

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[18] (ASTM, 2013)

fibers were removed from the water using fine screens and then placed in 750ml of water, where they were stirred using a plastic spoon (Figure 4). Their distribution while mixing was observed.

Figure 4: Stirring of cut sisal fibers in water

The Results

Stage one of experimentation yielded mostly qualitative results concerning the various types of fibers and their workability. All of the natural fibers were easy to clean and cut; sisal being the cleanest with regards to various entangled particles and dust. In particular, the hemp had straw and hay-like particulates embedded in the fibers and these different particles floated to the top and could be removed with a spoon (Figure 5).

Figure 5: Hemp cut fibers with particulates floating to the top when stirred

The sisal was more uniform as a material but although some particles floated to the top they were harder to remove, since much of the sisal also floated to the top while the water was stagnant. The 2nd quality jute was not a very uniform material; however it dispersed well in the water. The fibers could be stored for later use after they were cleaned and cut (Figure 6).

Figure 6: Compressed cut hemp fibers left to dry

3.2 Cut Fibers in Mixes

Observing that the fibers do indeed distribute well in the water while it is moving, it was important to see how the fibers would distribute in the concrete mix and if they would affect the aeration process. Other uncertainties include the amount of fibers that could be added before workability or aeration became a problem. Hemp, sisal, and qualities 1 and 2 of jute were used as well as graphite and glass fibers.

The Strategy

Two different mix ratios were poured for the natural fibers and one mix for each of the others (Table 3). The general concrete mix of Portland Cement Type I, quicklime powder, fly ash, aluminum paste, and water was complimented with either 8g or 12g dry weight of fibers. After all dry materials were measured; the fibers were placed in the water and stirred separately while the aluminum was added. The fibers, water, and aluminum where stirred constantly until poured into the final mix and stirred with a power drill paddle. It is important to note that if the speed on the drill is too high then the fibers clump on the mixing paddle. In such cases, mixing was stopped and the fiber clumps were removed from the paddle and re-added to the mix. If stirred slowly and simultaneously in a vertical up-down movement, the mix stirs and clumping in avoided. The mixes where then poured into lubricated standard cylinders until the cylinders were about three-fourths full and left to cure.

Table 3: Concrete mix ratios with cut fibers

Material	*Mix 1*	*Mix 2*
Water	750g	750g
PC Cement	500g	500g
Fly Ash	1000g	1000g
Lime	130g	130g
Aluminum Paste	2g	2g
Fibers (dry weight)	8g	12g

The cylinders were allowed to cure for a week. The maximum strength was not met at this time but the concrete mixes were not intended for strength testing. After curing, a small hole was punctured into the bottom of each cylinder and air pressure was used to push the concrete out of the molds. The concrete tended to overflow during curing (Figure 7); therefore the tops were cut using a bandsaw, creating a uniform volume.

The Results

The cylinders were then weighed and densities were documented (Table 4). After weighing the concrete cylinders, they were cut in half and fiber distribution and density variation was observed.

In comparison to the other fibers, the graphite fibers expand more in water for the same dry weight, whereas the glass fibers

Figure 7: Fiber cut concrete cylinders left to cure. From left to right, Jute No. 2 Mix 1, Jute No. 2 Mix 2, Hemp Mix 1, Hemp Mix 2, Jute No.1 Mix 1, Jute No. 1 Mix 2, Sisal Mix 1 and Sisal Mix 2.

would not separate from one and other in the water. The graphite fiber mixture also rose differently than the natural fibers. The mixture rose quickly and approximately 1.5 inches straight above the mold (Figure 8), rather than spill over as did the others. A possible explanation is the tightknit formation of the fibers with the concrete matrix, preventing the material to separate even at an early liquid stage.

Figure 8: Early rising of graphite fiber test cylinder

However, all other fibers distributed evenly in water and eventually within the concrete cylinders. The aeration of the concrete does not seem to be affected much by the natural fibers. In all the cylinders aeration still occurred as expected with a denser concrete on the bottom to a more aerated lightweight concrete on the top, as pictured held upside down in Figure 9.

Table 4: Chopped fiber concrete cylinder properties

Chopped Fibers	*Mix*	*height (inches)*	*weight (grams)*	*density (g/cm^3)*
Pulled Sisal	1	8	1347	0.82
Pulled Sisal	2	8	1475	0.90
Pulled Jute Quality No. 1	1	8	1376	0.84
Pulled Jute Quality No. 1	2	8	1331	0.81
Pulled Jute Quality No. 2	1	8	1210	0.73
Pulled Jute Quality No. 2	2	8	1354	0.82
Hemp	1	8	1263	0.77
Hemp	2	8	1295	0.79
Glass	2	8	1308	0.79
Graphite	2	8	1564	0.95

Figure 9: Sisal Mix 2 cylinder cut in half with the top closest to the camera lens

Experimental densities range from 0.73g/cm^3 to 0.89g/cm^3 (Table 4). The average density of concrete is 2.4 g/cm^3 and that of lightweight concrete is 1.75 g/cm^3. Typical values for this lightweight mix using fly ash without fibers would yield variable densities of 0.7-0.8 g/cm^3.

It is important to use these experimental densities as relative values, considering the time of curing varies between cylinders as do the fiber percentages. Clearer results would require several cylinders per mix.

3.3 Fiber Rope

Natural fiber rope can be used to replace the tensile steel reinforcement in beams or other structural members. Investigating how the rope will bind to the concrete will aid in designing such structural members. The concrete may fail to bind with the reinforcement, or it may vary the density of the aerated concrete surrounding it.

Regularly available fiber rope was tested with the general concrete mix. Sisal rope, although not the most durable of fibers, is readily available and used for a variety of reasons. Sisal rope in diameters of 3/8", ¼" and #390 was used for this experiment. Additionally, jute was also obtained with a diameter of 9/64". These ropes were all tested in the concrete in an effort to observe if the varying diameter thickness changes bonding. Rope water saturation levels were also varied for increased data.

The Strategy

These ropes, saturated and unsaturated, were secured in place before and the general concrete mix was added. The saturated ropes were simply soaked in water overnight. The concrete cylinders were lubricated to allow for easy release of the concrete from the molds. After drilling appropriate holes for the rope diameters through the bottom of the standard compression cylinders and through the top covers, the ropes were passed through, pulled taut, and secured using duct tape. Following placement of the rope, concrete was poured (Figure 10). These cylinders were only filled halfway due to expected aeration and rising.

The cylinders were allowed to cure for a week. Maximum strength was not achieved but the cylinders would not be strength tested. The concrete was removed from the molds; a small hole was punctured into the bottom of each cylinder and air pressure was used to push the concrete out of the molds.

Figure 10: Fiber rope cylinder molds left to cure. Sisal 3/8" unsaturated, Sisal 3/8" saturated, Sisal 1/4" unsaturated, Sisal 1/4" saturated (left to right)

The height of each was documented, along with the weight (Figure 11). The average density, considered over the full height of each cylinder, was calculated for each cylinder.

Figure 11: Fiber rope cylinders removed from molds. Weight and height of each is being recorded.

The cylinders were then sliced 2 inches from the base using a band saw. This 2inch think sample allowed for viewing the variation in radial density. The remaining upper half of each cylinder was then cut along its height, to note vertical variation of density.

The Results

Unfortunately, the fibers do not greatly vary the density around the rope. Experimental densities range from 0.94g/cm^3 to 1.05g/cm^3

(Table 5). The average density of the mixture is higher than that of the aerated concrete alone or of that with cut fibers, but that can be contributed to the increased fibers added within the tightly bound fiber rope. Additionally, there does not seem to be a relation between unsaturated and saturated rope in terms of density of the mix; in some cases the saturated rope mixes have a higher density and in others it does not make a difference.

Table 5: Properties of the fiber rope reinforced concrete cylinders

Fiber Rope	*Mix*	*height (in)*	*weight (g)*	*density (g/cm^3)*
Sisal 1/4"	saturated	5.5	1073	0.95
Sisal 1/4"	unsaturated	4.125	840	0.99
Sisal 3/8"	saturated	5.063	1073	1.03
Sisal 3/8"	unsaturated	4.375	850	0.94
Sisal #390	saturated	5	1080	1.05
Sisal #390	unsaturated	4.25	848	0.97
Jute 9/64"	saturated	5.25	1033	0.96
Jute 9/64"	unsaturated	4.625	915	0.96

The fiber rope changes the formation of the concrete. Saturated rope bonds to the concrete mix (Figure 12); whereas the unsaturated rope does not bond (Figure 13) and can slip through the entire cylinder when pulled with a significant force, such as that of a bandsaw blade spinning. All mixes rose less than expected, observed in the shorter heights of the concrete cylinders.

Figure 12: Saturated rope concrete cylinder sliced in half

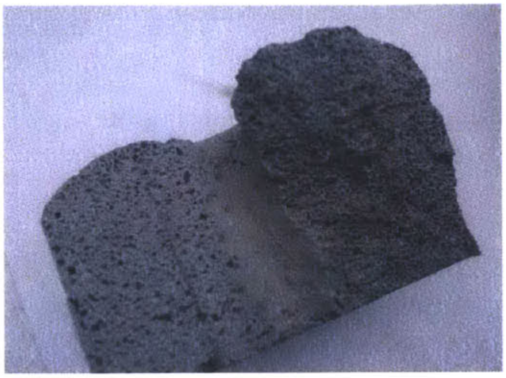

Figure 13: Unsaturated rope cylinder sliced in half after rope pulled from the cylinder

The fiber rope saturation results raise interest in how fiber woven fabrics would bond with the concrete. Would the concrete form through the layers of fiber and bond in such a way that would create a very flexible layer of concrete? Would more fiber rope or fabric effect the formation of the bubbles in the concrete directly linked to the fibers?

3.4 Aerated Concrete and Aggregate

Currently, as is, the general mix is quite expensive. Adding fine and coarse aggregates to concrete provides significant economic benefits, as well as effects on the hardened properties and mixture proportions. Aggregates often times compose 60-75% of the concrete volume in a mixture. They are the least expensive material used in concrete and they could make the aerated concrete mix less expensive and more realistic as a building material. The effects of aggregate on the aeration of the concrete are unknown.

Fine aggregates, such as sand, have a higher possibility of entering the spaces where air bubbles begin to form and preventing them from forming as expected. Coarse aggregate raises concerns about aeration as well. There is a possibility that the aggregates will be too heavy and will sink to the bottom during the early hours of curing when the aeration occurs. It is also possible that aeration doesn't occur if there is too much aggregate added to the mix. Discovering whether the concrete will aerate with various sizes of coarse aggregate will help give an understanding to the behavior of the mix. This early stage of understanding is a preliminary step in developing a lightweight concrete mix which includes a proper ratio of aggregate.

The Strategy

Coarse aggregate available in the lab was used for these initial experiments. Choosing aggregate that was not excessively large was important, since the standard cylinder molds would be used for the experiment and the large aggregate would really limit seeing the effects on the concrete in such a constrained volume. The aggregates were passed through sieves and organized into three size groups based on the majority of the largest particles in each group. These groups in increasing size were 0.187 in (4.75 mm), 0.25 in (6.3 mm), and 0.371 in (9.423 mm).

Figure 14: Coarse aggregate 0.371in group following separation

After the aggregates were separated into containers (Figure 14), the general proportions of aerated concrete mix were used; however as an experimental starting point, half of the Portland cement (dry mass) was replaced with aggregate. The dissolved aluminum and water were added to the mix and stirred using the drill attachment procedure from earlier experiments. Once the concrete looked well-mixed on its own, the aggregates were added and mixed in. Two control mixes of the standard cylinders without aggregate were poured three-fourths full and two cylinders were poured per aggregate size (Figure 15). All were allowed to cure to maximum strength.

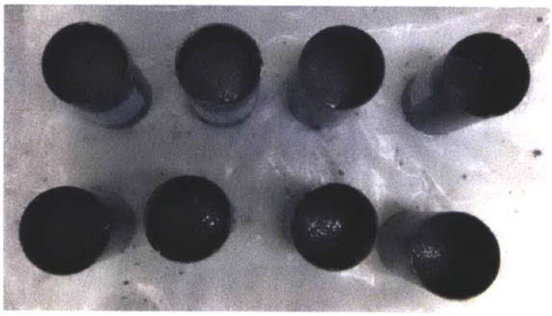

Figure 15: Aggregate and control concrete cylinders left to cure

Following a three week curing period, the concrete cylinders were removed from the molds using air pressure (Figure 16). It was necessary to cut the cylinders in half along their heights in order to observe aeration and aggregate distribution; however, unlike the general mix, the mix with aggregates could not be cut using the bandsaw.

Figure 16: Fully cured and de-molded concrete cylinders (left to right, control, 0.187", 1/4" and 0.371")

Indirect tension tests were conducted on the Baldwin-Tate-Emergy Testing Machine which is a 200,000lb machine. Thin black rubber sheets (3in by 9in) were placed along the top and bottom of the cylinders to ensure a proper connection with the machine (Figure 17). The load was lowered until it was barely touching the rubber sheet. Once contact was achieved between the two surfaces, the cylinders were loaded at a rate of 20,000lbs per minute, until failure.

Figure 17: Concrete cylinder positioned with rubber supports during indirect tension test

The Results

The quantitative results from the indirect tension tests indicate that there is a boundary at which point large aggregates negatively affect the bonding and tensile strength of the concrete (Table 6).

Table 6: Tensile failure of aggregate concrete cylinders

Mix	*Maximum Aggregate Size*	*Maximum Load (lbs)*
Control	none	1397
1	0.187 in (4.750 mm)	1626
2	0.250 in (6.300 mm)	1588
3	0.371 in (9.423 mm)	1217

Qualitatively, observations indicate that the concrete had risen during curing. Initial interpretations show that the aggregate did not have a negative effect on the aeration. Observations of the split cylinder, following the indirect tension testing, indicate that the aggregate has evenly distributed throughout the height of the cylinder. It is interesting to note that very few aggregates were elevated to the top portion which rose during curing. The aggregate sizes were small and close in range of size therefore it would be difficult to tell how larger aggregate would distribute or affect the aeration.

The distribution of these small aggregates indicates that more aggregates could be added into the general mix. There is a limit however before the aeration is affected, but further experiments could find a proper mix.

3.5 Smooth Surface Molds

The aerated concrete mix inevitably forms a rough surface due to the aeration and constantly rising level of concrete during the early hours of curing (Figure 18). Once the mix is used to form beams, blocks or other structural members, it will be important that all sides can be formed with smooth surfaces. The aerated concrete itself can be cut using a bandsaw with a diamond blade, however, once aggregate is added to the mix, cutting a section becomes difficult and dangerous. It may be possible to scrape off the top of the mold and smooth the surface before the concrete is fully cured and hardened; however the key is not to affect the aeration.

Figure 18: Cylinder samples mid-experiment

The purpose of the experiment is to identify a time frame during which scraping off the overflowing aerated concrete can be done relatively easily and most importantly allows for normal aeration throughout the mixture.

The Strategy

Twelve cylinder samples were poured, two per test, using the normal concrete mix and no aggregates. Two cylinders were kept as the control, leaving the top as it naturally forms. The tops of the remaining ten cylinder samples were removed in 1.5 hour intervals, in some cases varying the removal method used. A thin wire was used in combination with a triangular trowel, in an attempt to remove the top layers evenly and cleanly (Figure 18). It was important to pour all cylinders from the same mix in an attempt to eliminate uncertainties with varied aeration that could develop. The general mix was used in a larger batch (Table 7) adequate for six test cylinders and ensuring overflow that could be scraped.

Table 7: Proportioning the general mix for larger batches

Material	*Quantity (grams)*
Water	3375
PC Cement	2250
Fly Ash	4500
Lime	585
Aluminum	9

This larger batch made using the drill paddle a bit more challenging, but with a strong arm and patience, it was still possible to homogeneously mix the concrete without requiring a large mixer. Ensuring that no dry material is left around the edges of the mixing bin is essential. Any larger batch size would require the use of a cement mixer to ensure proper mixing.

The Results

The first set of cylinders smoothened 1.5 hours after pouring were still aerating and it can be seen that the mixture is too liquid to properly remove the top and the process collapses all the bubbles that are still forming (Figure 19).

Figure 19: Cylinder sample smoothened after 1.5 hours (S5 No. 2)

Table 8: Observations during surface smoothening of sample concrete cylinders

Cylinder Sample	*Curing Time (hours)*	*Observations*
Control 2 No.1	--	Aerated as in previous experiments
Control 2 No.1	--	Aerated as in previous experiments
S5 No.1	1.5	Still really wet; the trowel was used but that ripped off chunks of concrete.
S5 No.2	1.5	Still really wet; the trowel was used to cut all but the top 1/2 inch and then the wire was used to slowly scrape off layers; this created a smooth finish but may have caused the top layer to compact.
S6 No.1	3	Starting to solidify; the trowel was used to scrap almost all off then the wire was used to make a clean cut.
S6 No.2	3	Same method as above, but smoother result.
S7 No.1	4.5	Becoming hard on top; harder to remove top layer with trowel; previous method still works.
S7 No.2	4.5	Same as above.
S8 No. 1	6	Very similar to hour 4.5 cylinders.
S8 No. 2	6	Same as above.
S9 No. 1	7.5	Difficult to smoothen with wire.
S9 No. 2	7.5	Same as above.

Qualitative results from this experiment are summarized with notes in Table 8 while the final cylinders can be seen in Figure 20.

Figure 20: All twelve cylinders after curing (Control 2 No.1 to S9 No.2, left to right)

The best method identified to remove concrete layers from the top of the molds consists of two parts. First, layers of the concrete must be removed using a trowel or some other large, strong, flat surface. Once approximately a quarter of an inch remains above the mold, a thin wire may be pulled across the surface to evenly cut the material without removing large pieces from inside the mold. The material accumulated on the wire can easily be removed, with light pressure to push it off.

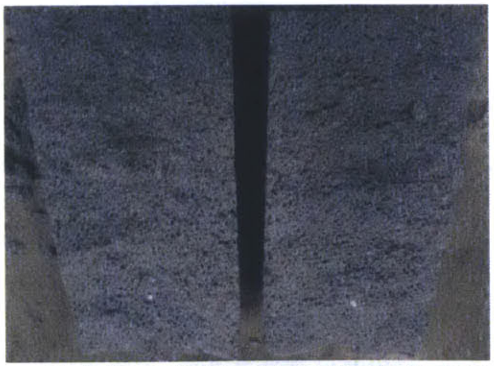

Figure 21: Cylinder S9 No.2 following the indirect tension test

The latter cylinders follow a variable density pattern similar to that of the control experiments (Figure 21) implying that the time frame for removing the top layer avoids harming the aeration.

The overall densities of the final concrete cylinder samples give an initial idea as to whether aeration is affected during the smoothening process. There seems to be a decreasing trend in density as the cylinder is left untouched during the early hours of curing (Figure 22). Minimal effects of aeration combined with workability (Table 8) would suggest that the ideal time frame for removing the uneven top of a mold is between six and seven hours after pouring. This time still allows the chemical reaction to aerate and form the concrete without severe effects to bubble formation and without solidifying and preventing a smooth removal.

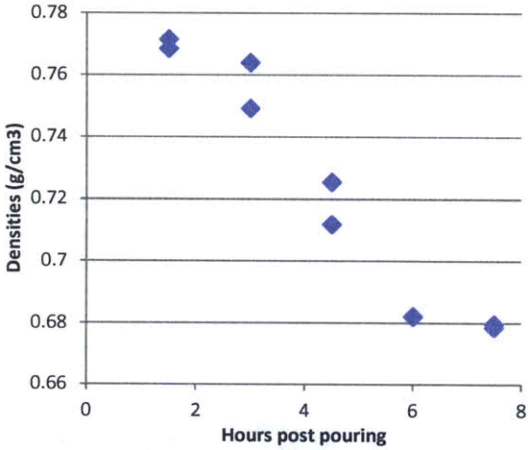

Figure 22: Densities of aerated concrete after curing for several hours before being interrupted

Indirect tensile load tests were conducted on the cylinders with the procedure used to test the aggregate cylinder in Section 3.4 to allow us to view the bubble matrix formation. The results of the maximum tensile load before the cylinders split in half can be seen in Figure 23. The results indicate that the latter two cylinders, cured for six to eight hours before scrapping off material, have a 0.5kN tensile strength higher than the control. This could very well be coincidental, since all the cylinders were poured from the same mix. It could also be something that requires more experimentation in the matrix structure of the air bubbles.

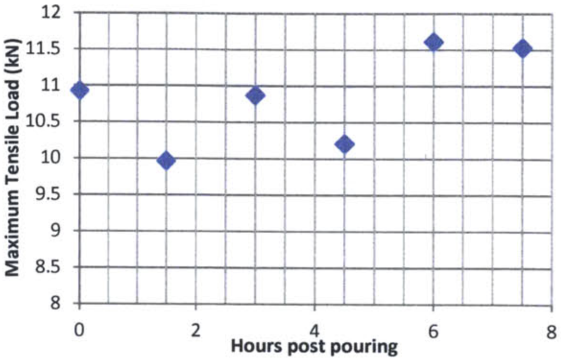

Figure 23: Maximum tensile load of aerated concrete after curing for several hours before being interrupted

Perhaps, the effect of scrapping the top as opposed to cutting it at the end, allows for greater aeration at the top following removal. It is possible that the overflowing material which solidifies on the top of the control cylinder inhibits the aeration from continuing after a certain point, whereas removing the material allows it to continue.

3.6 Compression Lab Testing

Compression testing the cylinders will give peak load capabilities and a modulus of elasticity for these mixes. The cylinders have been cured for over 28 days so they can be a source of additional information for understanding exactly how these additives are affecting the original aerated concrete mix. Values obtained can also serve as a comparison to normalweight concrete.

Strategy

All twelve concrete test cylinders were allowed to cure to 28-day strength. The aggregate cylinders from Section 3.4 were also allowed to cure and similarly arranged to be tested. The uneven top was removed from the control cylinder using the bandsaw. All other cylinders had been smoothened during the previous experiment and were ready for loading. The even top ensures distributed loading of the test specimen in the compression machine. In the case where a top or bottom of a mold is rough or uneven, a layer of gypsum plaster or plaster of Paris can be added to create a smooth surface. This process however was unnecessary in these experiments. The compression tests were conducted using an instrumented hydraulic ram loading the samples to failure. Strain gauges were attached to the cylinders (Figure 24), as was a data recording computer to track elongation with respect to the added load.

This procedure was repeated for all the cylinders from Sections 3.4 and 3.5. This data was taken and represented via graphs using a spreadsheet. Graphs of stress vs. strain were then used to analyze the modulus of elasticity of the material.

Figure 24: Concrete cylinder sample ready for compression loading

Results

Quantitative results from the non-aggregate and aggregate cylinders were analyzed separately. The control cylinders for both experiments indicate a maximum compressive strength of 1.3-1.5MPa for the aerated concrete general mix, however modulus of elasticity and other properties vary greatly between cylinders.

Non-aggregate Concrete

For the twelve cylinders without aggregates, some of the samples exhibited hysteresis behavior and found different load paths after experiencing one failure. The overall results are quite varied (Table 9), some reach a peak and regain strength (Figure 25) following similar behavior of metals while others gain peak strength after failing once.

This seems to imply that different load paths can be formed once certain air spaces collapse. This indicates that the cellular concrete has a more ductile failure than normal concrete and that the cellular matrix allows the material to absorb the initial impact better. The key is discovering where and why there are differences and how to control the behavior.

Table 9: Summary of results from compressive loading of smooth surface cylinders

Sample	*Maximum Compressive Stress (MPa)*	*Strain at Failure (mm/mm)*	*Modulus of Elasticity 1 (MPa)*	*Modulus of Elasticity 2 (MPa)*	*Modulus of Elasticity 3 (MPa)*	*Modulus of Elasticity 4 (MPa)*
Control 1 N2	1.51	.00126	1313.7			
S1N2	1.96	.00504	849.1	277.3	189.4	
S2N2	1.42	.00208	715.3			
S3N2	1.67	.00241	769.8			
S4N2	1.07	.00336	542.2	145.0	208.2	432.7
Control 2 N2	1.53	.00157	863.2	199.2	301.5	
S5N2	1.24	.00377	612.3	456.2	396.2	
S6N2	1.69	.00350	1201.7	530.0	241.9	
S7N2	.99	.00147	653.9	25.9	54.9	
S8N2	1.065	.00200	563.7			
S9N2	1.24	.00118	899.6			

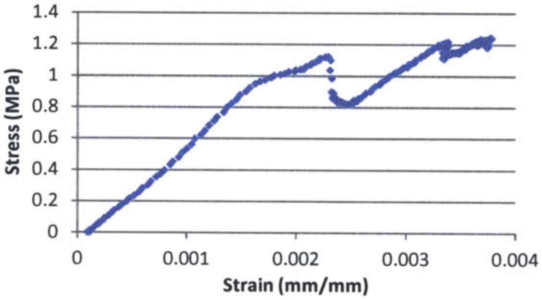

Figure 25: Stress vs. strain for concrete cylinder S5N2, left to cure for 3 hours before smoothened

The maximum compressive strength of both control cylinders, left to cure untouched, is consistent around 1.5MPa, but the modulus of elasticity varies from 1300MPa to 860MPa, with various methods of failing (Figure 26). The other compressive strengths vary from 1MPa to approximately 2MPa, with no consistent pattern with respect to curing time or modulus of elasticity.

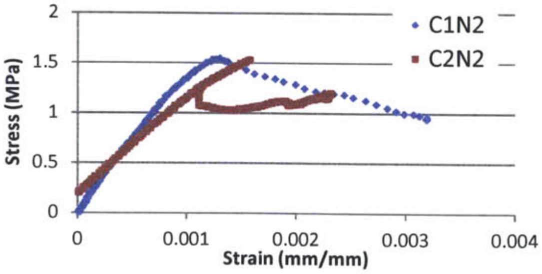

Figure 26: Stress vs. strain curves for control concrete cylinders

It is important to note that although these max compressive strengths are relatively low in comparison to other concretes, all cylinders remain in one piece when removed from the machine (Figure 27). Though fracture lines can be seen along the exterior of the cylinders, the internal fracturing seems to be at varied locations in such a way that allows the other parts of the solid to remain intact. This behavior is similar to the toughening effect of adding cut fibers to concrete as discussed in Chapter 2.

Figure 27: Concrete cylinder S6 No.2 post compression testing, still in one piece

Further tests should be conducted to identify a pattern or connection between strength and disrupting the curing. For consistency, several cylinders should be tested for each interval.

Aggregate Concrete

The cylinders with aggregate likewise had varied results. As expected, all three concrete samples with added aggregate had higher strength than the control, with 0.371" aggregates providing a 25% increase in strength (Figure 28). However, this reduces the ductility of the material and leads to sudden fracture. The 0.25" cylinder sample can be seen following the compression test in Figure 29. Here it can be seen that the cylinder broke into pieces in comparison with the non-aggregate cellular concrete cylinders which remained in one piece (Figure 27).The increase in strength and modulus of elasticity is not consistently related to an increase in aggregate size, since the 0.25" aggregate performed worse than the 0.137" aggregate. Speculation leads to relating this anomaly to the exact distribution of the aggregate within the sample. This implies it is not related to the size, in which case a detailed conclusion cannot be reached on the effects of the different aggregate sizes with respect to strength of the overall specimen.

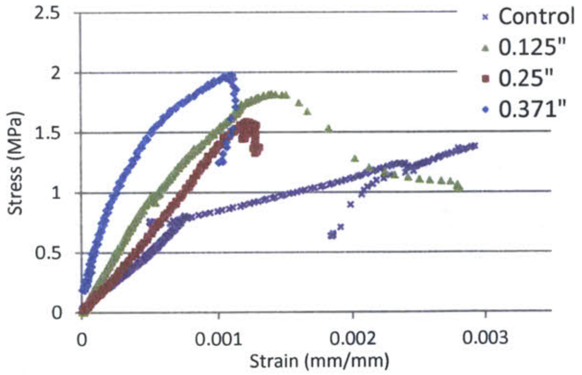

Figure 28: Stress vs. strain curves for aggregate cylinders and control

Overall it seems that the aggregate limits the ability of bubble formation. The aggregate properly distributes homogenously throughout the mold however the ability for the aggregate to be carried to the surface as the concrete rises adds pressure to the matrix and prevents the air bubbles. The aggregates replace the air gaps in the concrete, so although it adds strength to the concrete, it is no longer a lightweight aerated concrete. The added ductility gained by the cellular matrix is also lost

Figure 29: 0.25" aggregate concrete cylinder post compression testing

4. Conclusions

This work demonstrates that variable density lightweight concrete mixtures have room for improvement. More importantly the results substantiate that the concrete still aerates after adding aggregate and reinforcement to the concrete mix. The effects on the variable density throughout the samples, is less with the addition of fibers than with aggregate. Cut fibers and aggregate disperse and mix evenly throughout the matrix of the test samples. Creating regular prefabricated structural members is a possibility with the ability to remove spill-over layers from molds within a six to eight hour time frame. This would allow a prefabrication factory, to run a machine holding a wire cutter along the edge and across the top surface of a curing mold, without affecting the formation of the cellular material. This procedure could possibly increase the aeration and cellular matrix formation within the top few inches of a mold.

Future Work

The next steps in this investigating process would include the design of small beams and slabs using an appropriate aggregate concrete mix and adding fiber rope reinforcement (Figure 30). The rope would replace the steel rebar normally used in concrete beam design. This rope could be pre-tensioned until the beam is cast and cured. The beam will need to be cast upside down seeing as the gravity forming method of this lightweight concrete creates a variable density which decreases with the height of the cast.

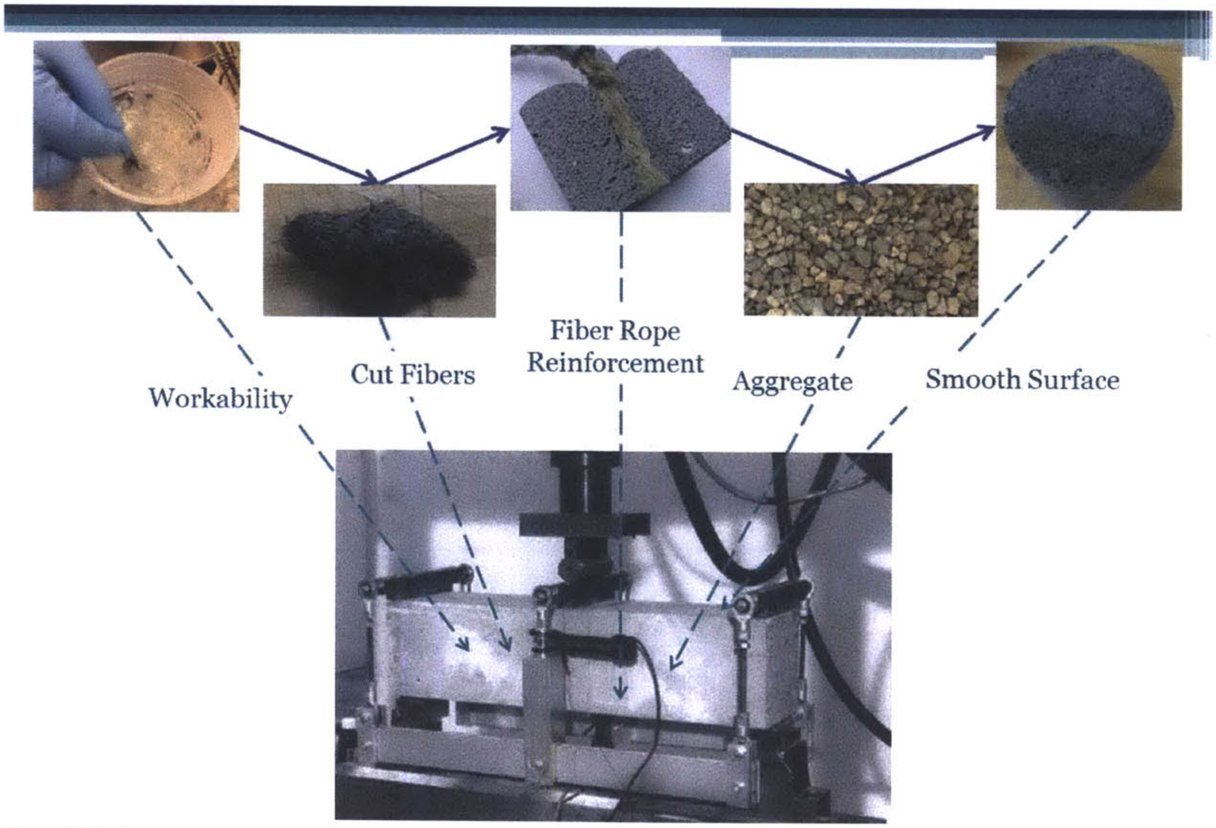

Figure 30: Summary of research in relation to future work of a concrete beam to be tested in three-point bending

The less dense region of the beam should be the section primarily containing the tensile fiber reinforcement; whereas the denser region of the beam should be on the compression portion of the beam. Design of structural members will pose a question concerning the scalability of this research. How will these methods and procedures scale for larger mix proportions and projects? This will need to be investigated further.

Preliminary research has also been conducted using woven sisal fiber fabric. The idea being that this fabric will be able to handle tension in two directions similar to two-way slab design. The fiber fabric could provide a very flexible, yet strong concrete. Fiber fabric can be found commercially for preliminary testing, although this woven fiber is of a much higher quality than is needed for construction.

Additional research should be conducted concerning deterioration of the natural fibers within the concrete members. It is possible that dampness and acidity could "destroy" the fibers in which case a pretreatment process to prevent such outcomes might be necessary.

Contributions

The research and ideas outlined in this thesis provide a beginning for developing inexpensive strengthening methods and reinforcement for variable density lightweight concrete, in the form of aggregate additives and natural fibers. The idea overall has room for further experiments and repetitive testing, however the results from these investigations give a preliminary understanding of material workability, experimentation methods and topics of focus. The focus of these investigations has been in creating a concrete with low embodied energy, using fly ash and curing at room temperature, while simultaneously adding reinforcement with low embodied energy. This concrete could be very suitable in developing nations where steel reinforcement is too expensive and often times unavailable.

References

Ancient Rope Bridges. (2013, February 4). Retrieved from Spotlight: http://www.spotlightradio.net/listen/ancient-rope-bridges

Aïtcin, P.-C. (September 2000, September). Cements of yesterday and today: Concrete of tomorrow. *Cement and Concrete Research*, 1349-1359.

ASTM. (2013). *Annual Book of ASTM Standards: Concrete and Aggregates.* Retrieved from ASTM Web Site: www.astm.org

Coburn, A. W. (2002). *Earthquake Protection.* Chichester, UK: Wiley.

Cooke, T. G. (2012). *Lightweight Concrete: Investigations into the Production of Variable Density Cellular Materials.* Cambridge, MA: Massachusetts Institute of Technology .

Crow, J. M. (March 2008). The Concrete Conumdrum . *Chemistry World*, 62-66.

Ho, J. C. (2012). Experimental Tests on High-Strength Concrete Columns Subjected to Combined Medium Axial Load and Flexure. *Advances in Structural Engineering*, 1359-1374.

Kramme, M. (2012). *Mayan, Incan, and Aztec Civilizations* . Quincy, IL: Mark Twain Media, Inc., Publishers.

Malhotra, V. M. (2000). Role of Supplementary Cementing Materials in Reducing Greenhouse Gas Emissions. In G. O. K, *Concrete Technology for a Sustainable Development in the 21st Century* (pp. 226-235). London: E & FN Spon.

Mindess, S. (2008). Fibrous concrete reinforcement. In S. Mindess, *Developements in the formulation and reinforcment of concrete* (pp. 154-166). Cambridge, UK: Woodhead Publishing Limited.

Mindess, S. (2008). Introduction. In S. Mindess, *Developments in the formulation and reinforcement of concrete* (pp. xiii-xiv). Cambridge, UK: Woodhead Publishing Limited.

Portland Cement Association. (2013). *Cement and Concrete Basics.* Retrieved from Portland Cement Association Web Site: http://www.cement.org/basics/index.asp

VanderWerf, P. A., Panushev, I. S., Nicholson, M., & Kokonowski, D. (2006). *Concrete Systems for Homes and Low-Rise Construction.* New York New York: McGraw-Hill Companies, Inc.

Appendix A: Images

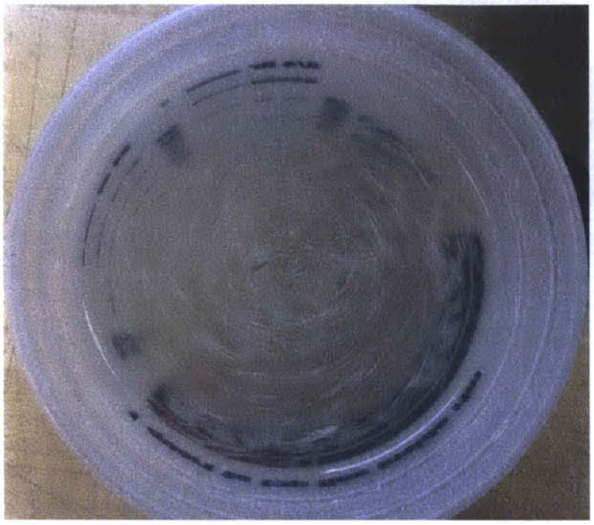

Figure 31: Sisal mixing in water

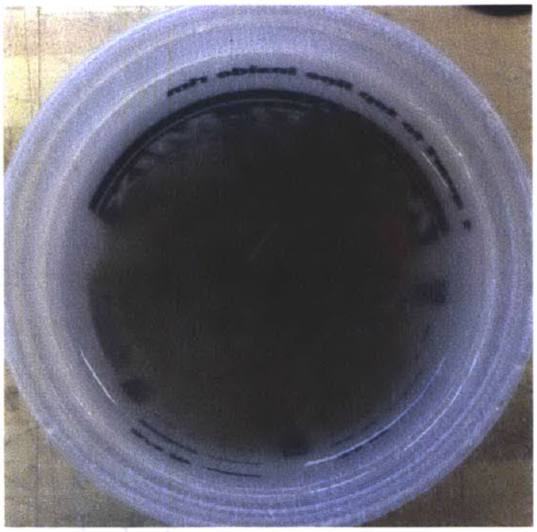

Figure 33: Hemp mixing in water

Figure 32: Jute No.1 mixing in water, noting particles floating to surface

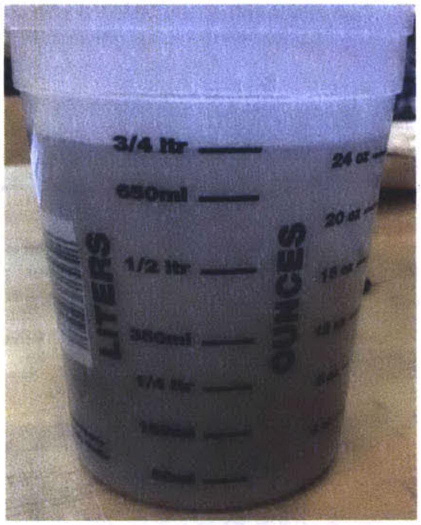

Figure 34: Even distribution of fibers throughout mix

Figure 35: Natural cut fiber concrete mixes left to cure

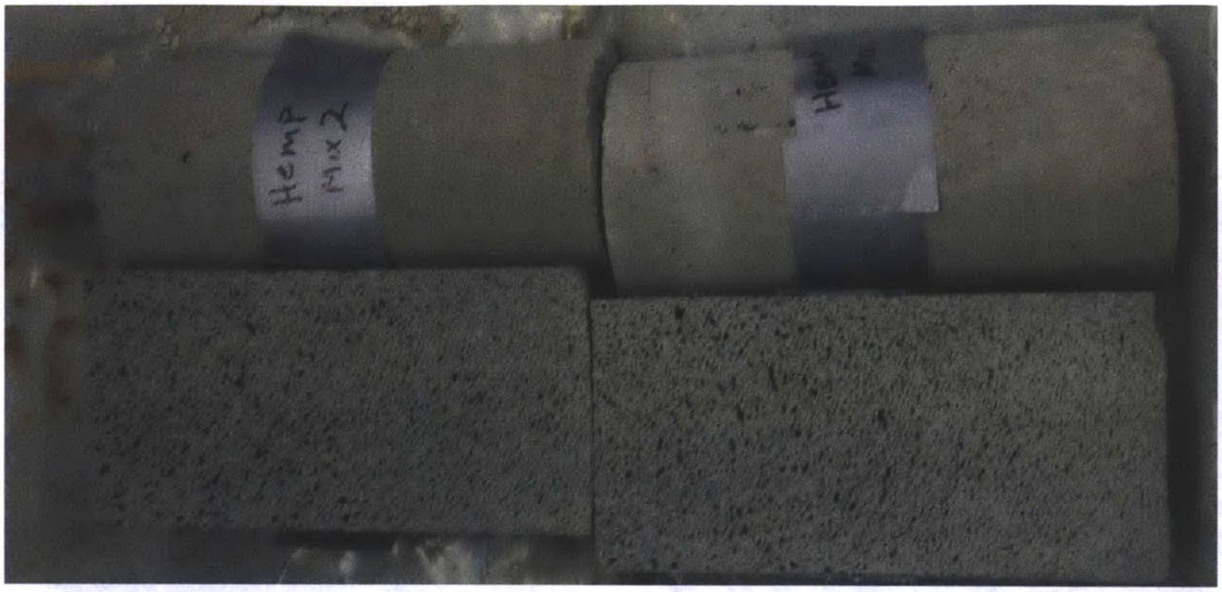

Figure 36: Comparison of hemp cut fiber mix 2 and mix 1 (left to right)

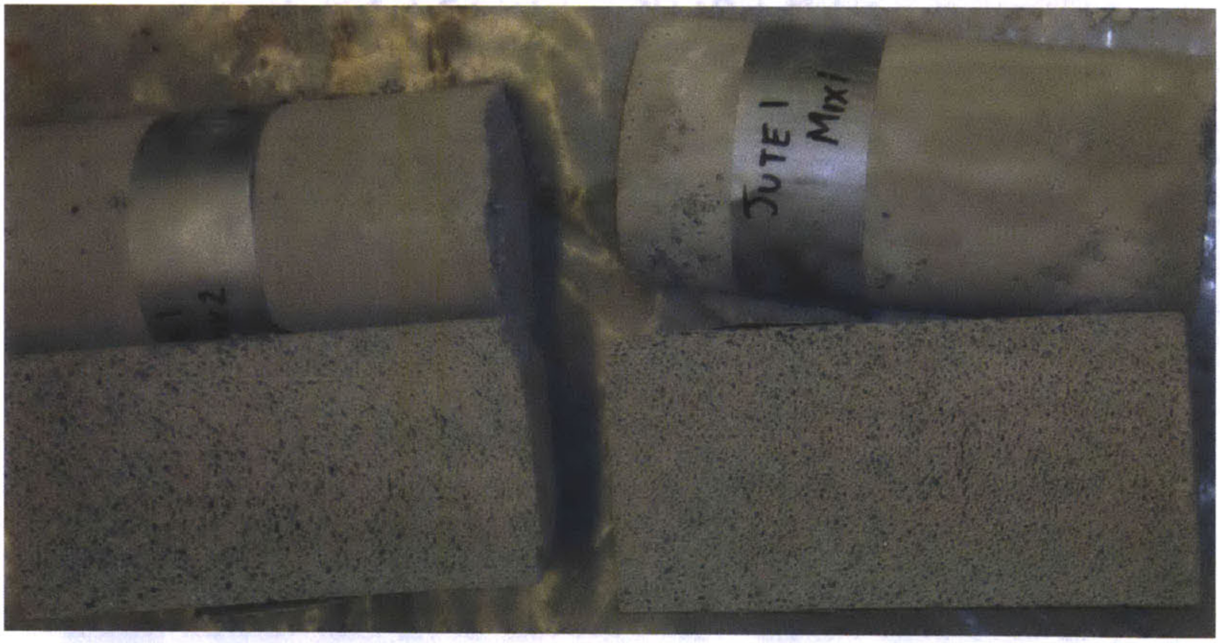

Figure 37: Comparison of June No. 1 cut fibers mix 2 and mix 1 (left to right)

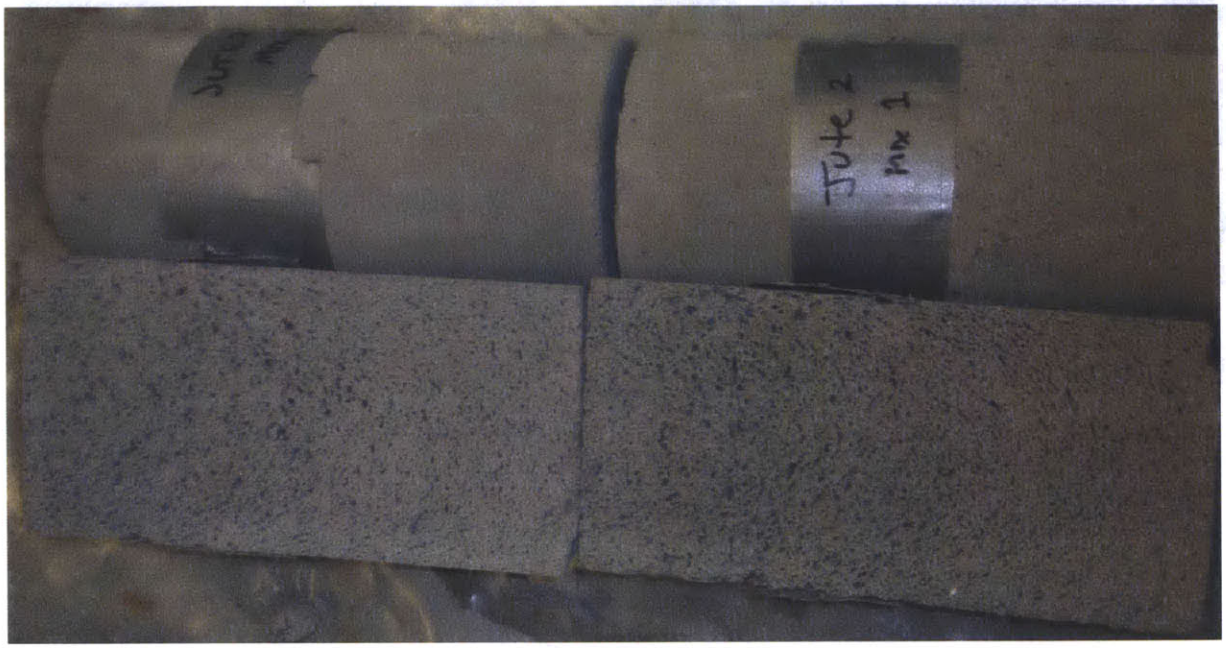

Figure 38: Comparison of Jute No.2 cut fibers mix 2 and mix 1 (left to right)

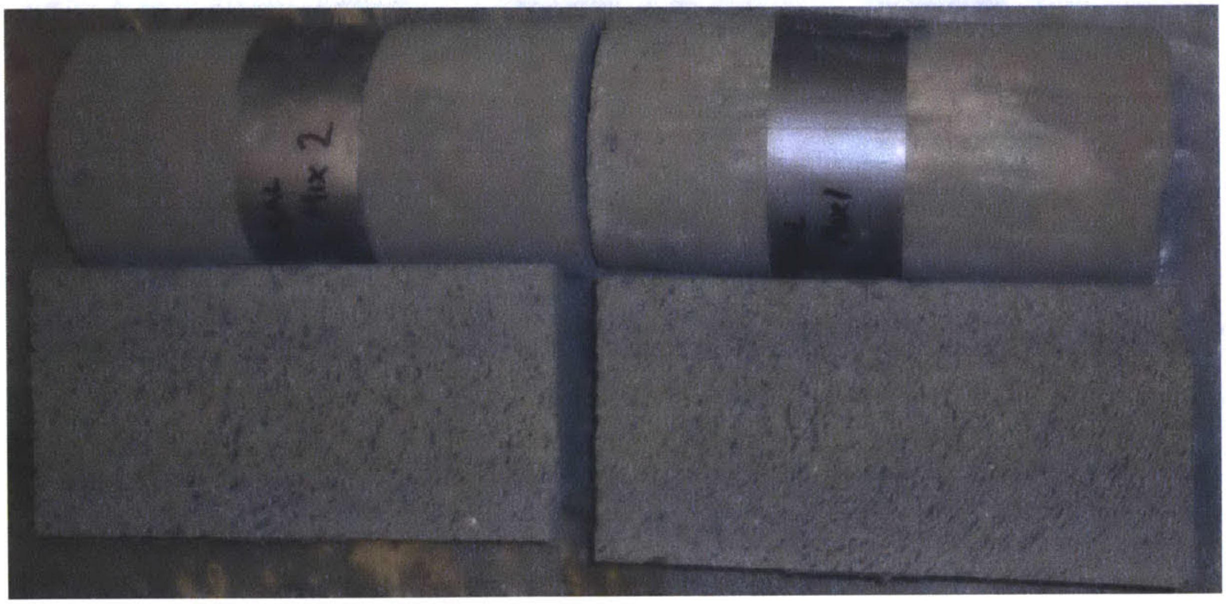

Figure 39: Comparison of Sisal cut fiber mix 2 and mix 1 (left to right)

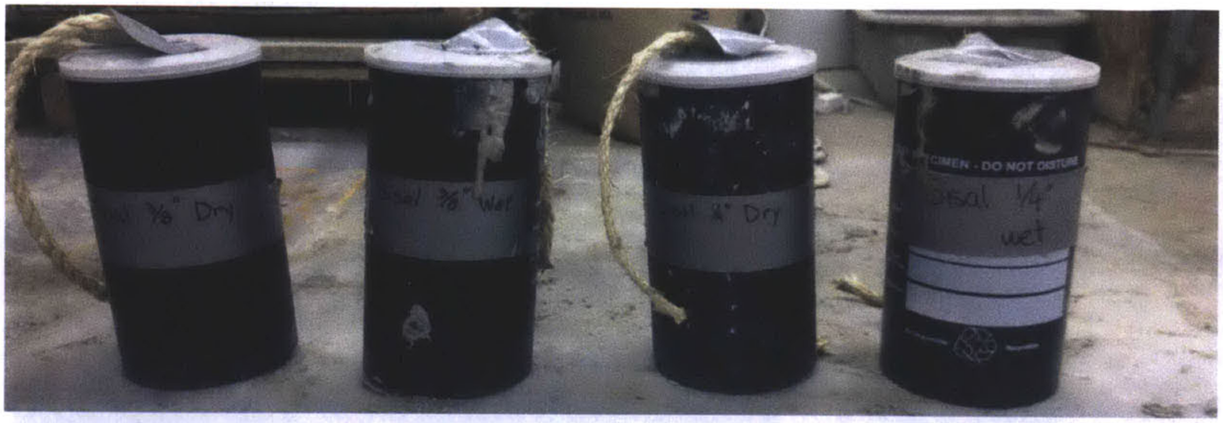

Figure 40: Fiber rope concrete cylinders left to cure (From left to right, Sisal 3/8" unsaturated, Sisal 3/8" saturated, Sisal 1/4" unsaturated, Sisal 1/4" saturated)

Figure 41: Fiber rope concrete cylinders left to cure (From left to right, Jute 9/64" saturated, Jute 9/64" unsaturated, Sisal #390 saturated, Sisal #390 unsaturated)

Figure 42: Unsaturated sisal fiber rope concrete cylinder

Figure 43: Saturated sisal fiber rope concrete cylinder

Figure 44: Research presentation of early experiments

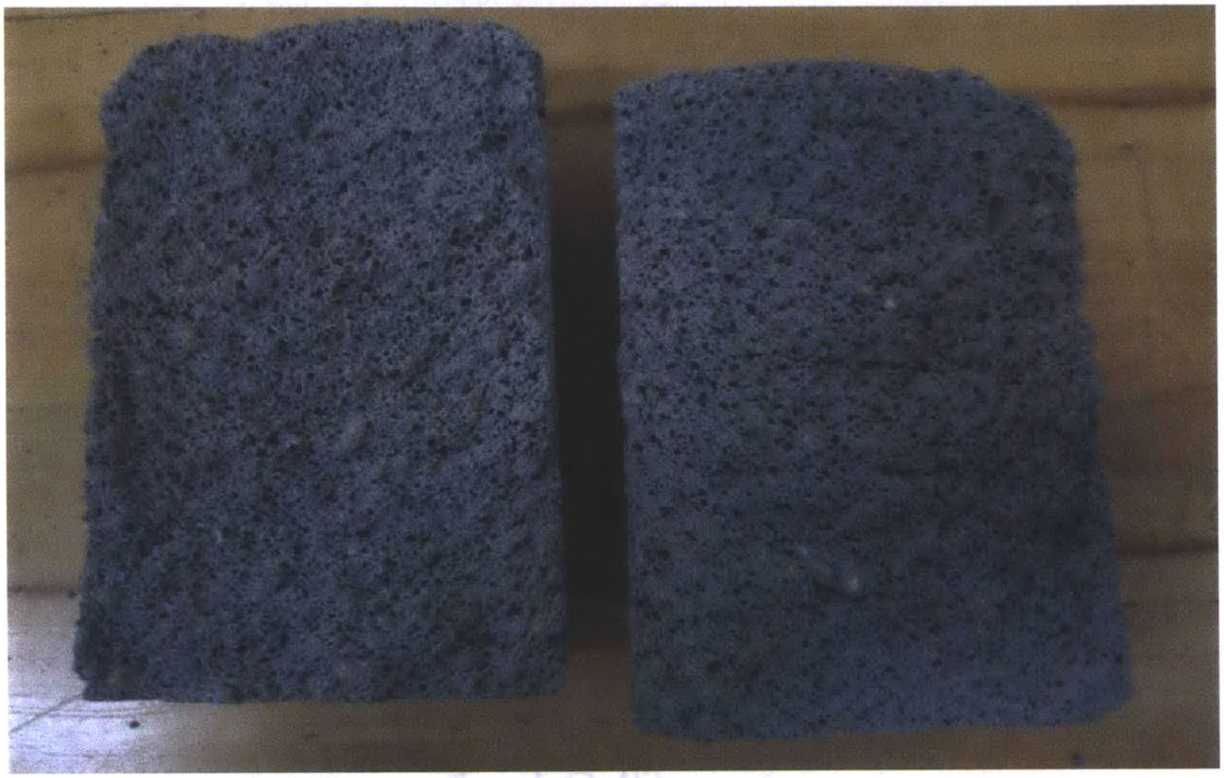

Figure 45: 0.25" aggregate concrete cylinder post indirect tension testing

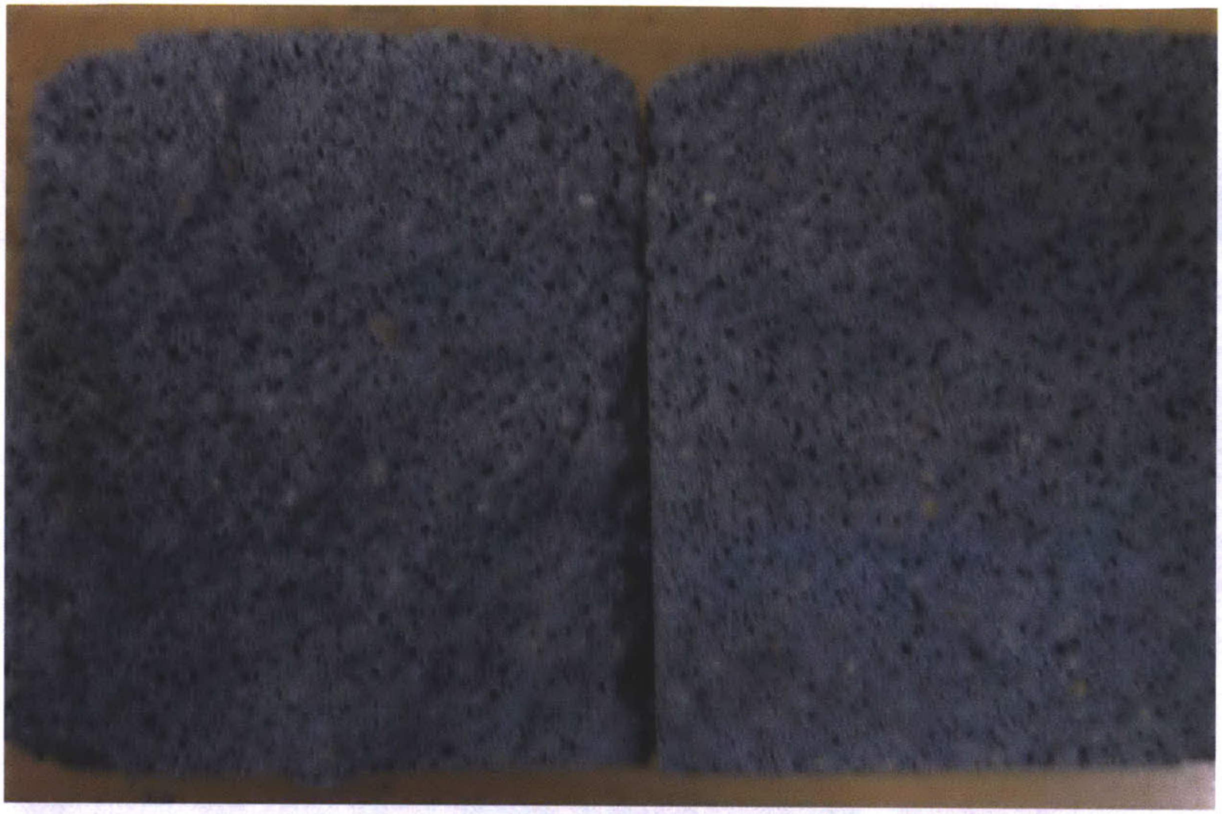

Figure 46: 0.125" aggregate concrete cylinder post indirect testing

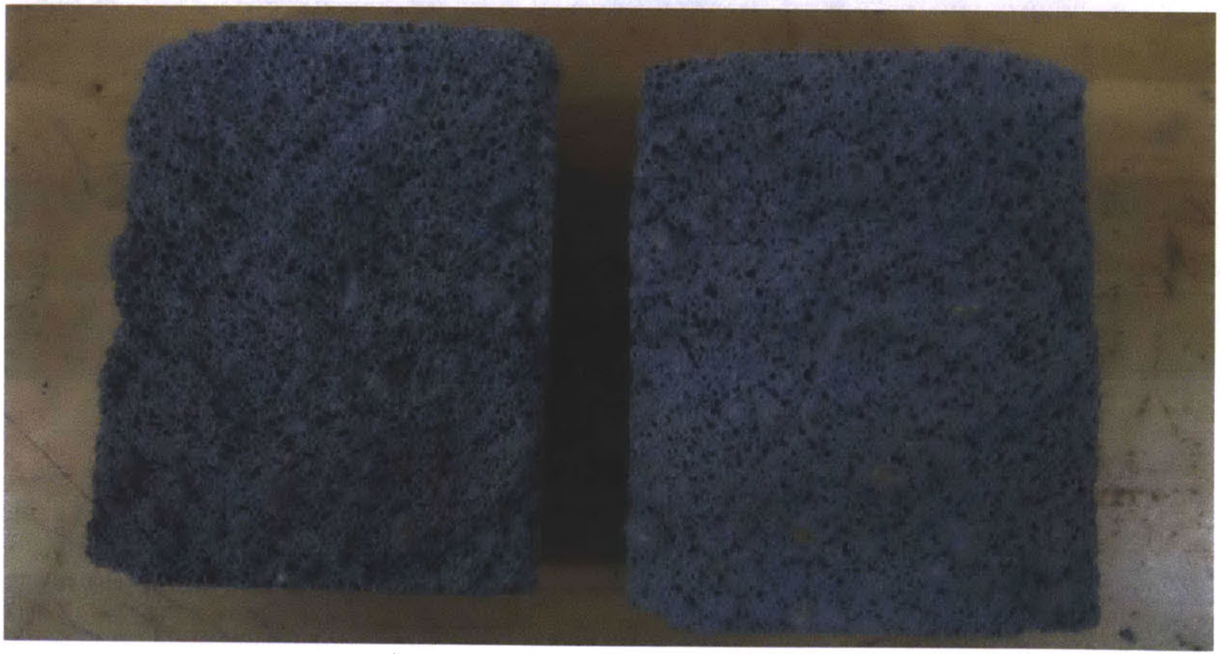

Figure 47: 0.371" aggregate concrete cylinder post indirect tension testing

Figure 48: Cylinder S6N2 post compression testing

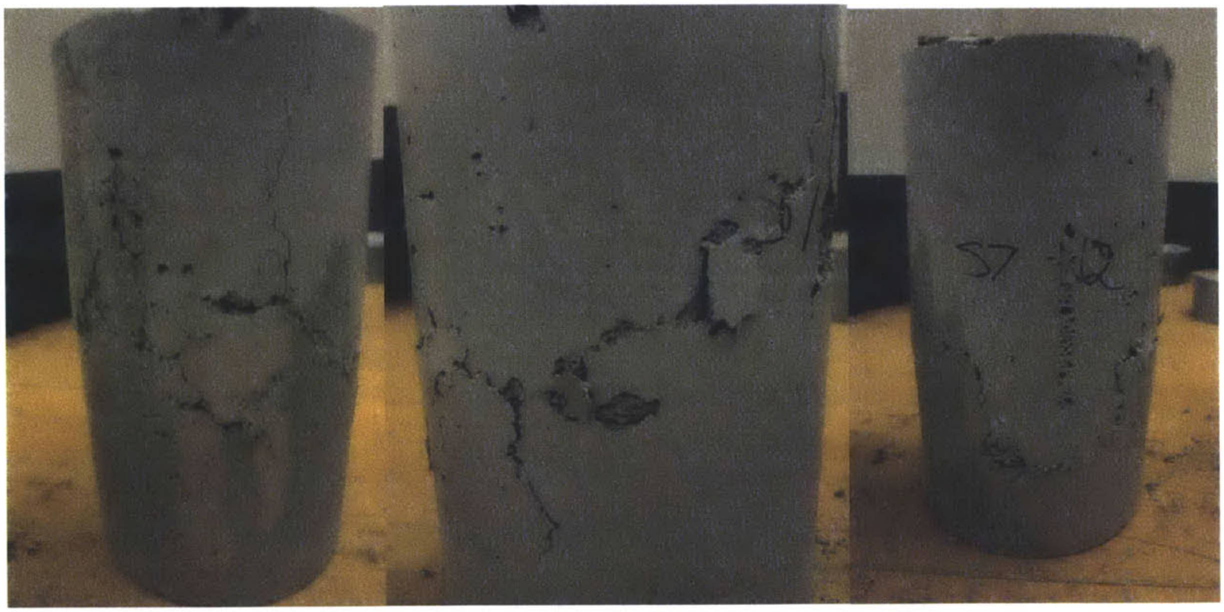

Figure 49: Cylinder S7N2 post compression testing

Appendix B: Compression Test Results

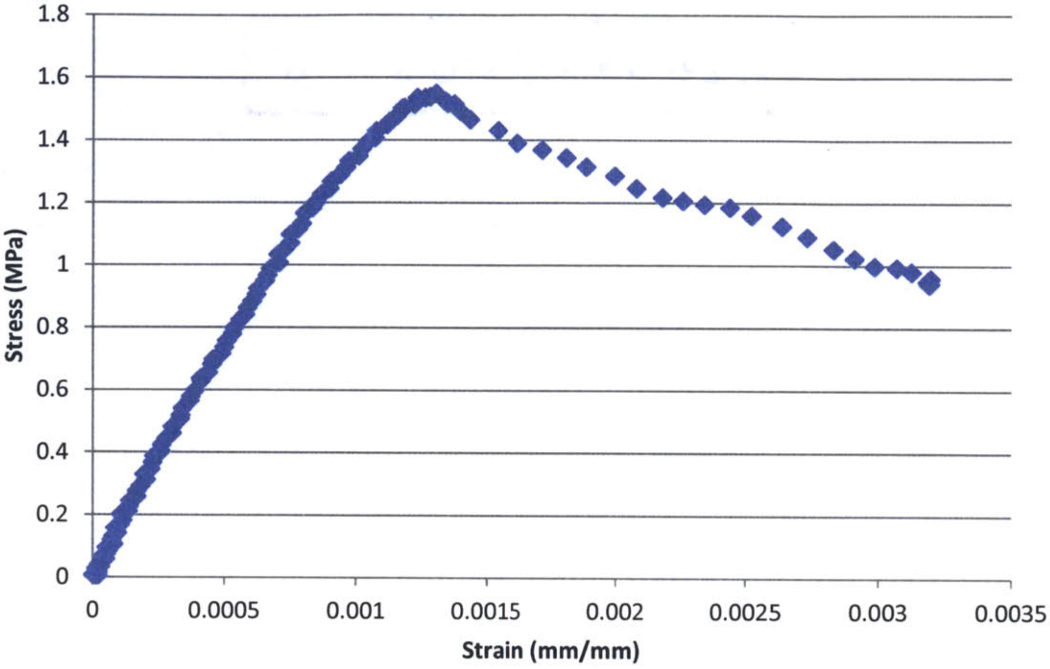

Figure 50: Stress vs. strain curve for Control 1 No.2 test cylinder, indicating a maximum compressive strength of 1.5MPa

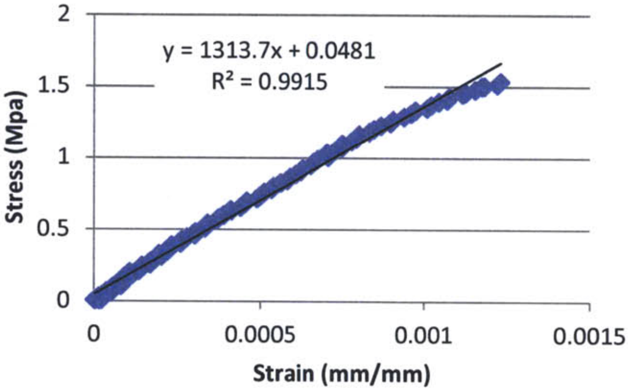

Figure 51: Modulus of elasticity calculation for Control 1 No.2 cylinder, indicating a modulus of elasticity of 1313MPa

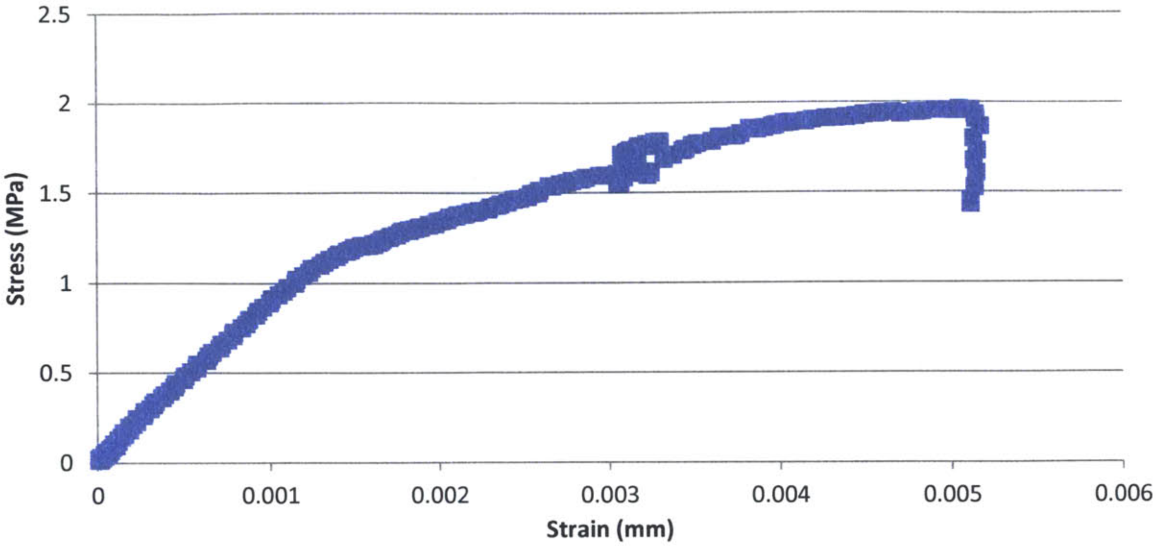

Figure 52: Stress vs. strain curve for the S1N2 test cylinder, indicating a maximum compressive strength of 2MPa

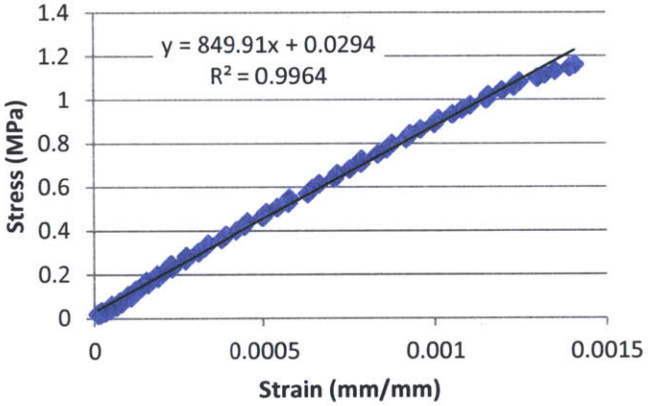

Figure 53: Modulus of elasticity calculation for the S1N2 test cylinder, indicating a primary modulus of elasticity of 850MPa

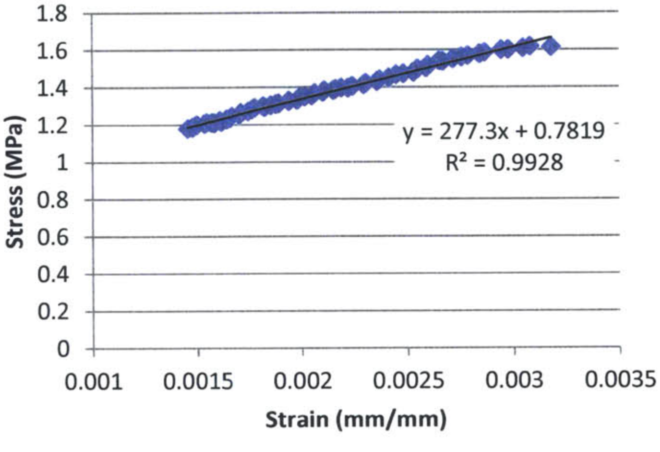

Figure 54: Modulus of elasticity calculation for the S1No2 test cylinder, indicating a secondary modulus of elasticity of 277MPa

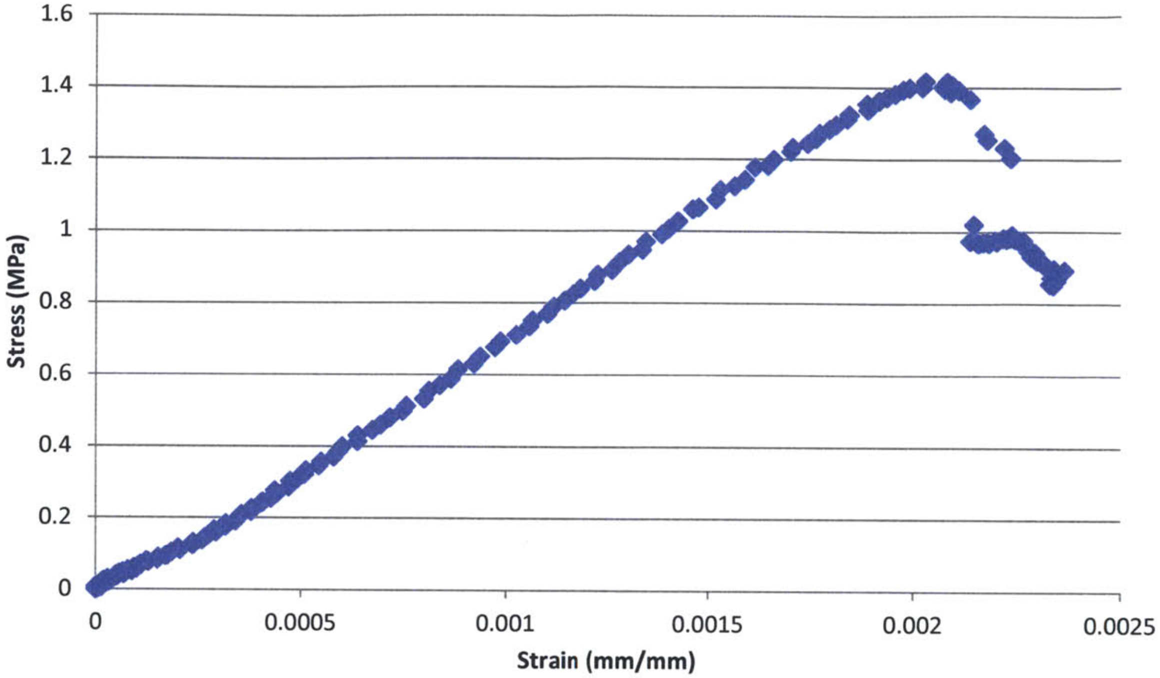

Figure 55: Stress vs. strain curve for the S2N2 test cylinder, indicating a maximum compressive strength of 1.4MPa

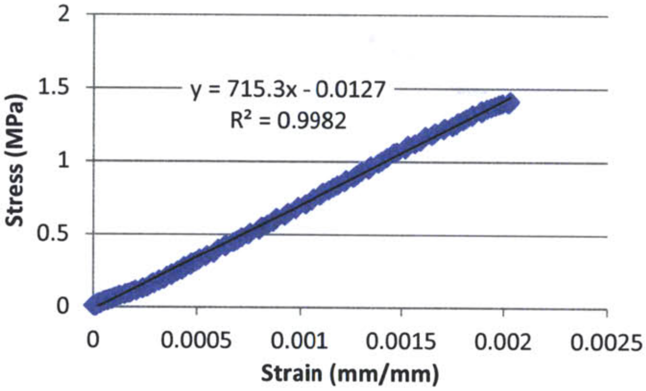

Figure 56: Modulus of elasticity calculation for S2N2 cylinder, indicating a modulus of elasticity of 715MPa

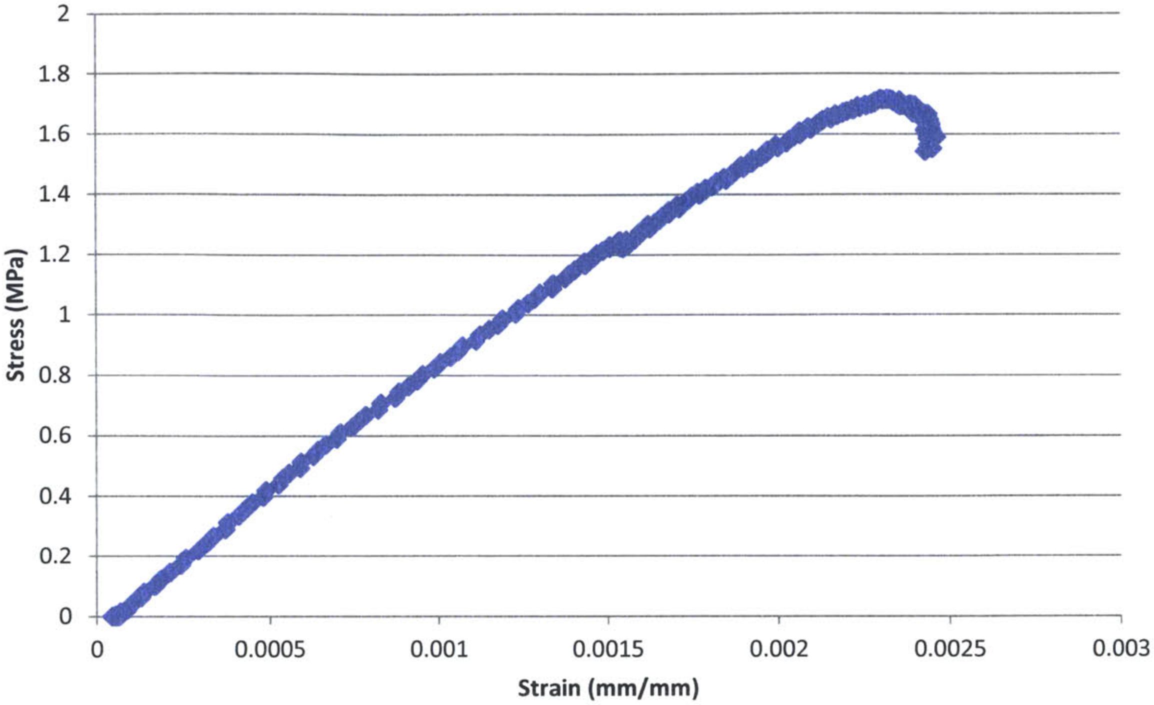

Figure 57: Stress vs. strain curve for the S3N2 test cylinder, indicating a maximum compressive strength of 1.7MPa

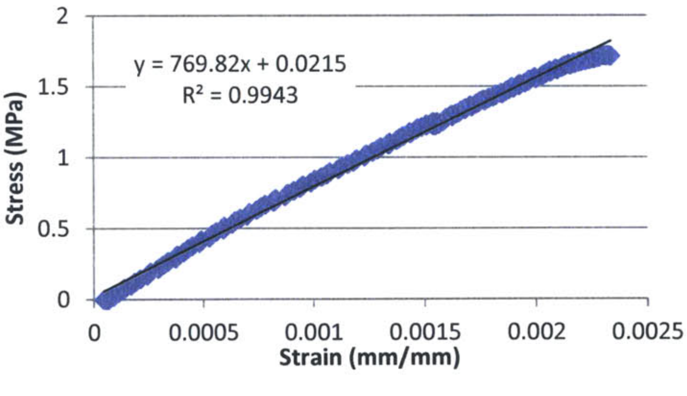

Figure 58: Modulus of elasticity calculation for S3N2 cylinder, indicating a modulus of elasticity of 770MPa

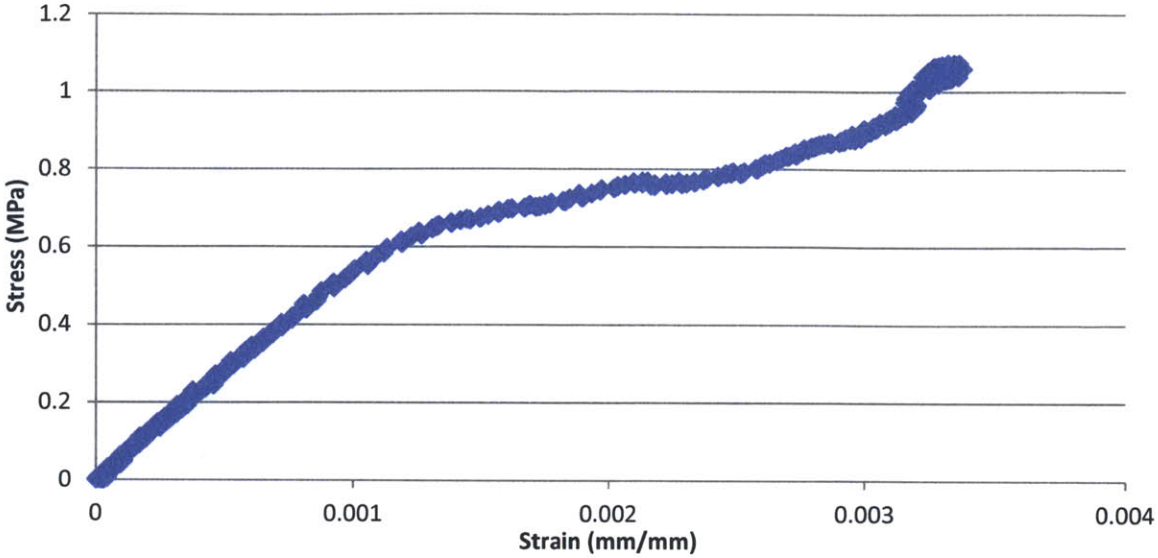

Figure 59: Stress vs. strain curve for the S4N2 test cylinder, indicating a maximum compressive strength of 1.1MPa

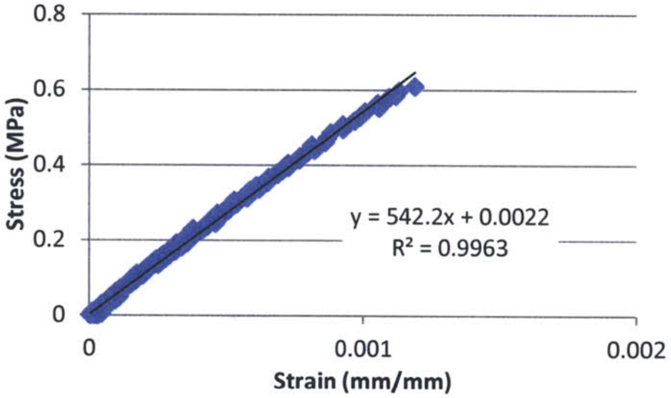

Figure 60: Modulus of elasticity calculation for the S4N2 test cylinder, indicating a primary modulus of elasticity of 542MPa

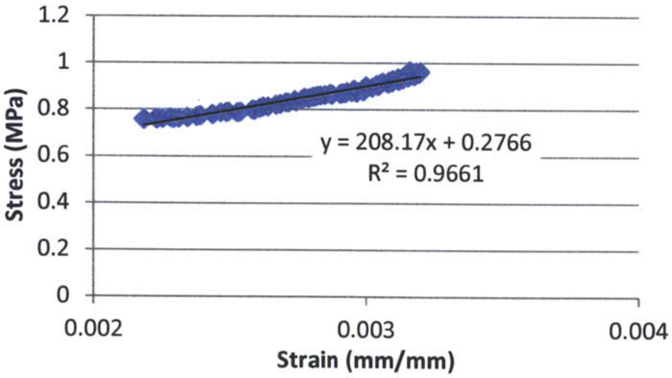

Figure 61: Modulus of elasticity calculation for the S1N2 test cylinder, indicating a secondary modulus of elasticity of 208MPa

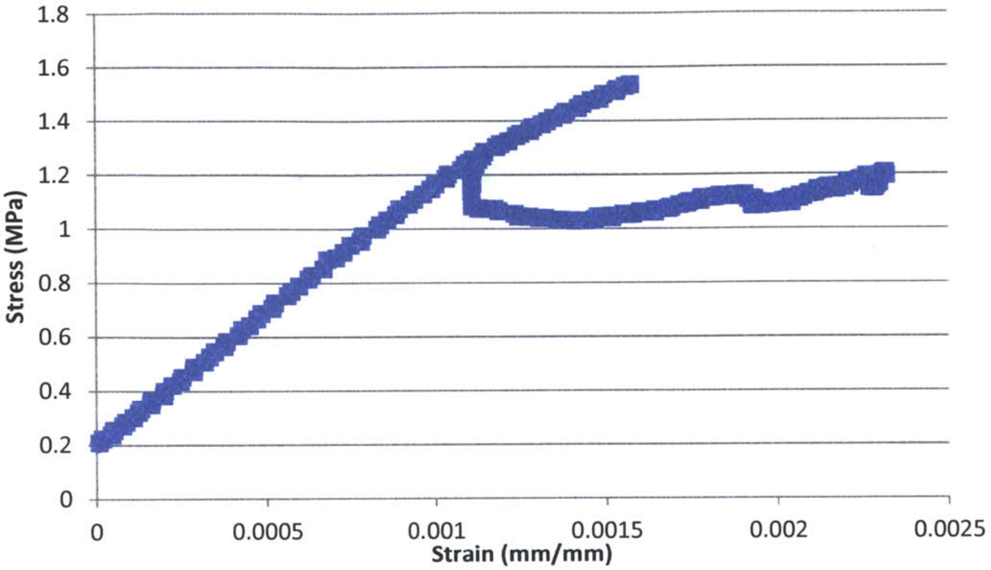

Figure 62: Stress vs. strain curve for the C2N2 test cylinder, indicating a maximum compressive strength of 1.6MPa

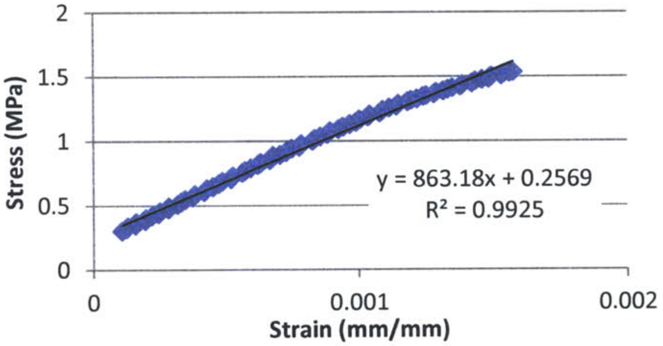

Figure 63: Modulus of elasticity calculation for the C2N2 test cylinder, indicating a primary modulus of elasticity of 860MPa

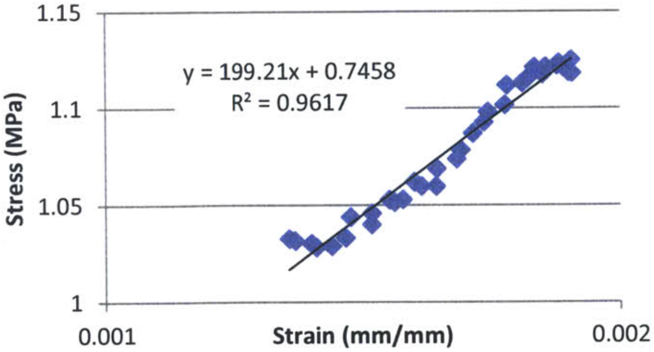

Figure 64: Modulus of elasticity calculation for the C2N2 test cylinder, indicating a secondary modulus of elasticity of 200MPa

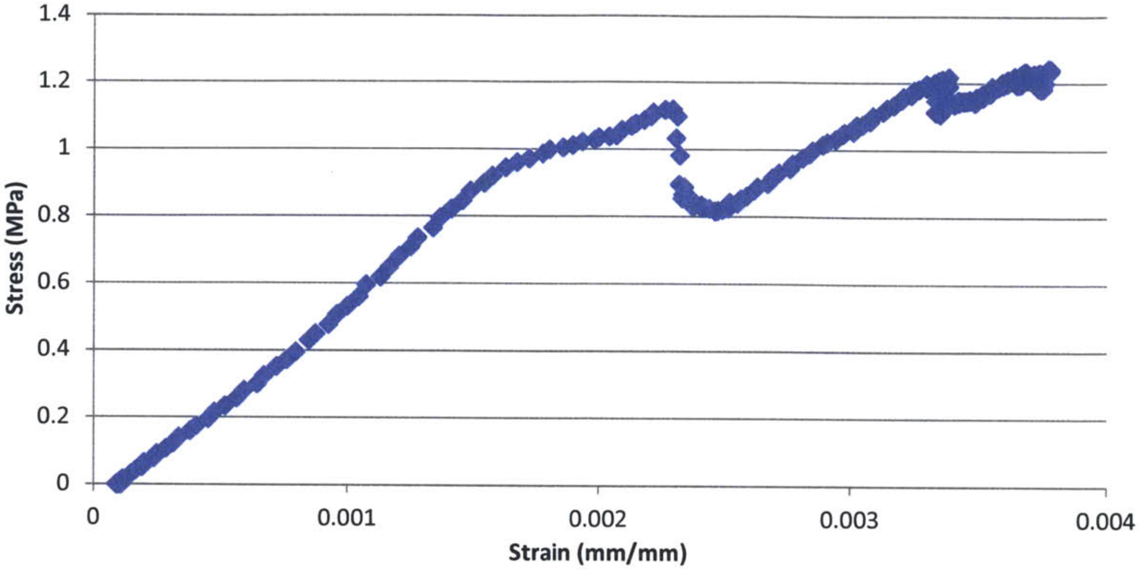

Figure 65: Stress vs. strain curve for the S5N2 test cylinder, indicating a maximum compressive strength of 1.3MPa

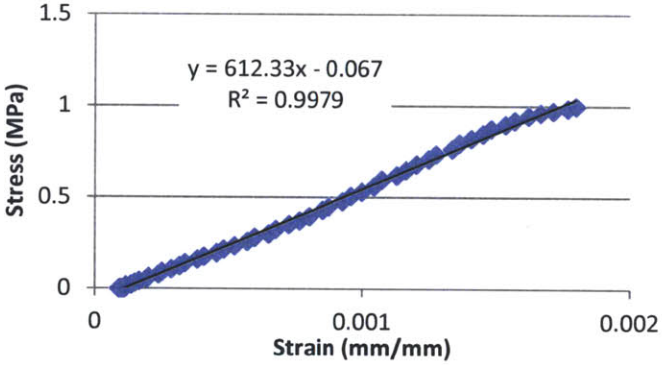

Figure 66: Modulus of elasticity calculation for the S5N2 test cylinder, indicating a preliminary modulus of elasticity of 610MPa

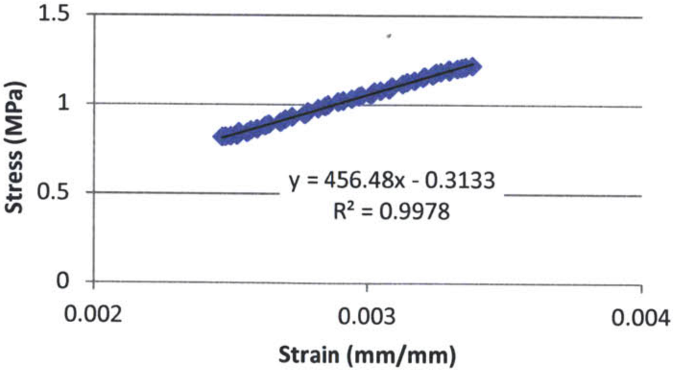

Figure 67: Modulus of elasticity calculation for the S5N2 test cylinder, indicating a secondary modulus of elasticity of 460MPa

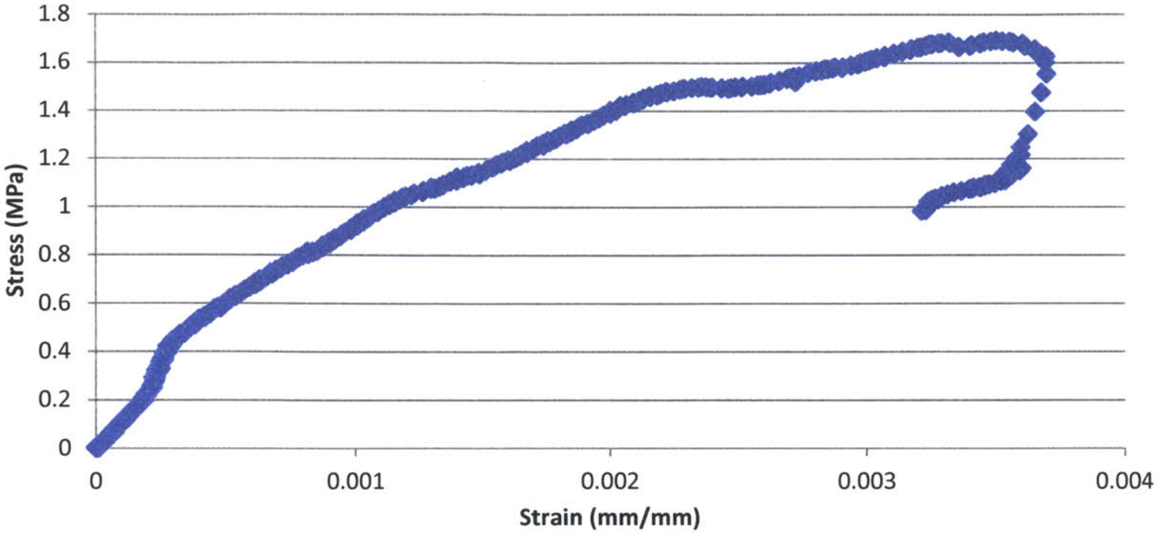

Figure 68: Stress vs. strain curve for the S6N2 test cylinder, indicating a maximum compressive strength of 1.7MPa

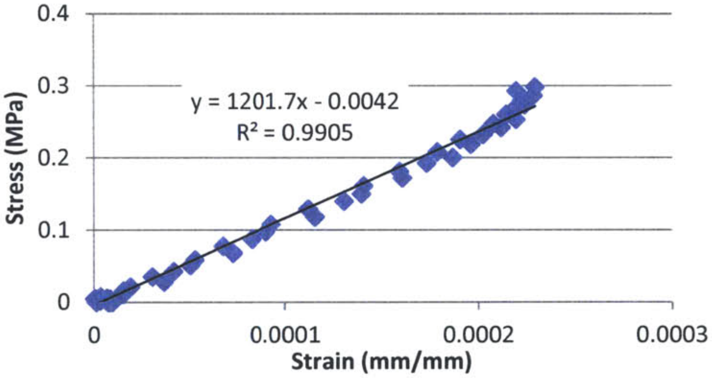

Figure 69: Modulus of elasticity calculation for the S6N2 test cylinder, indicating a preliminary modulus of elasticity of 1200MPa

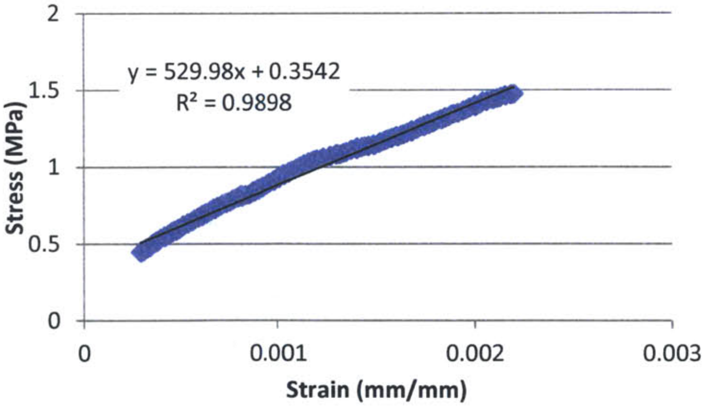

Figure 70: Modulus of elasticity calculation for the S6N2 test cylinder, indicating a preliminary modulus of elasticity of 1200MPa

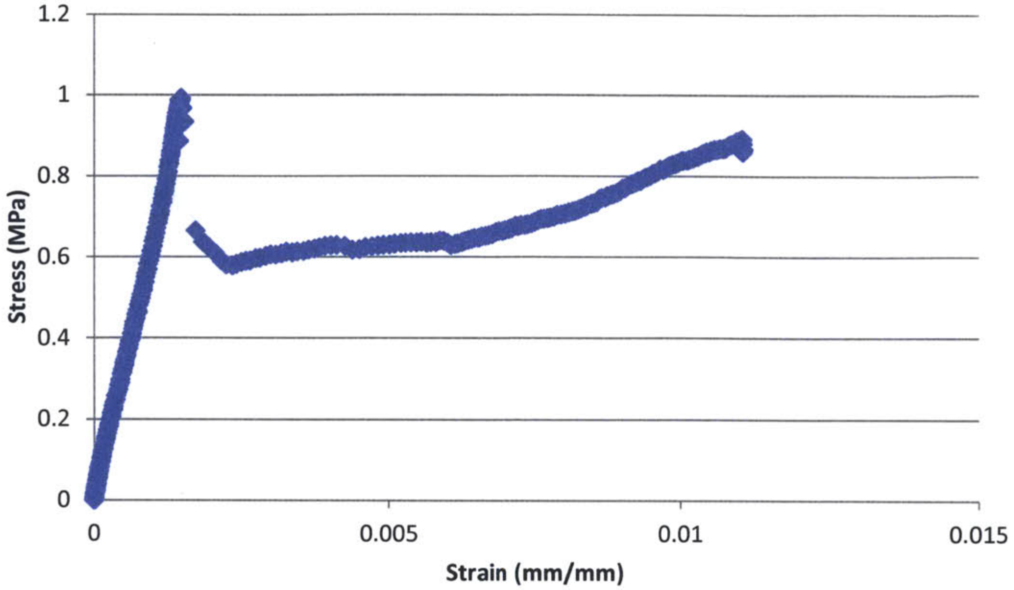

Figure 71: Stress vs. strain curve for the S7N2 test cylinder, indicating a maximum compressive strength of 1MPa

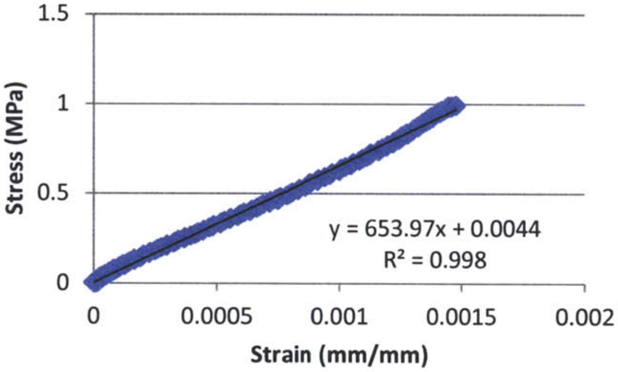

Figure 72: Modulus of elasticity calculation for the S7N2 test cylinder, indicating a preliminary modulus of elasticity of 650MPa

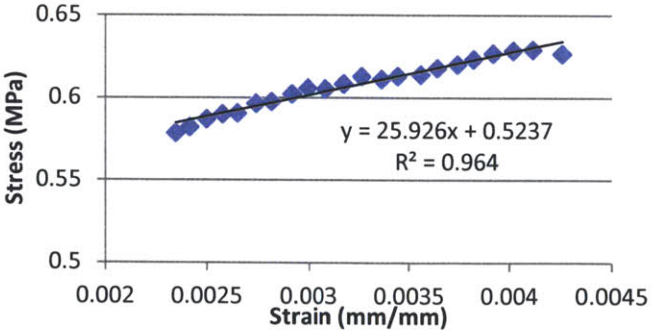

Figure 73: Modulus of elasticity calculation for the S7N2 test cylinder, indicating a preliminary modulus of elasticity of 26MPa

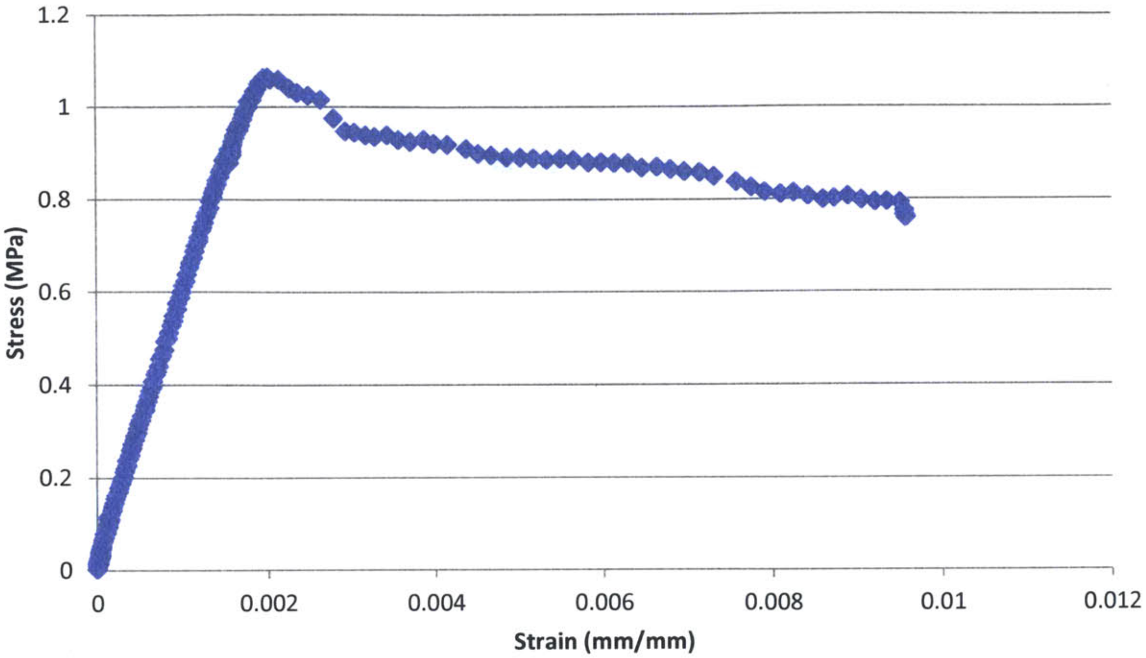

Figure 74: Stress vs. strain curve for the S8N2 test cylinder, indicating a maximum compressive strength of 1.1MPa

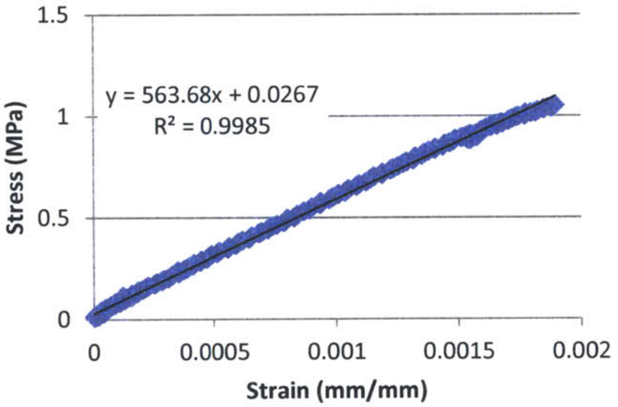

Figure 75: Modulus of elasticity calculation for the S8N2 test cylinder, indicating a modulus of elasticity of 560MPa

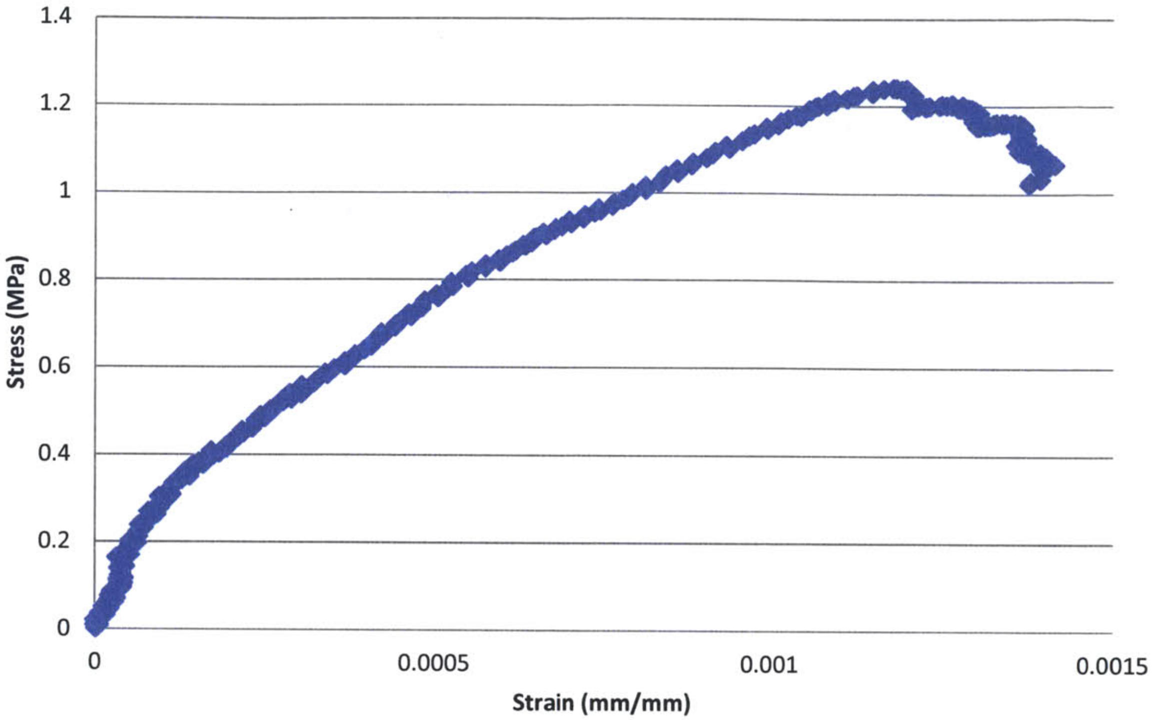

Figure 76: Stress vs. strain curve for the S9N2 test cylinder, indicating a maximum compressive strength of 1.3MPa

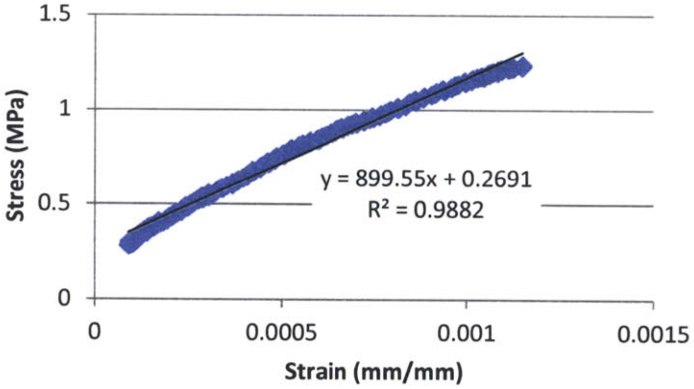

Figure 77: Modulus of elasticity calculation for the S9N2 test cylinder, indicating a modulus of elasticity of 900MPa

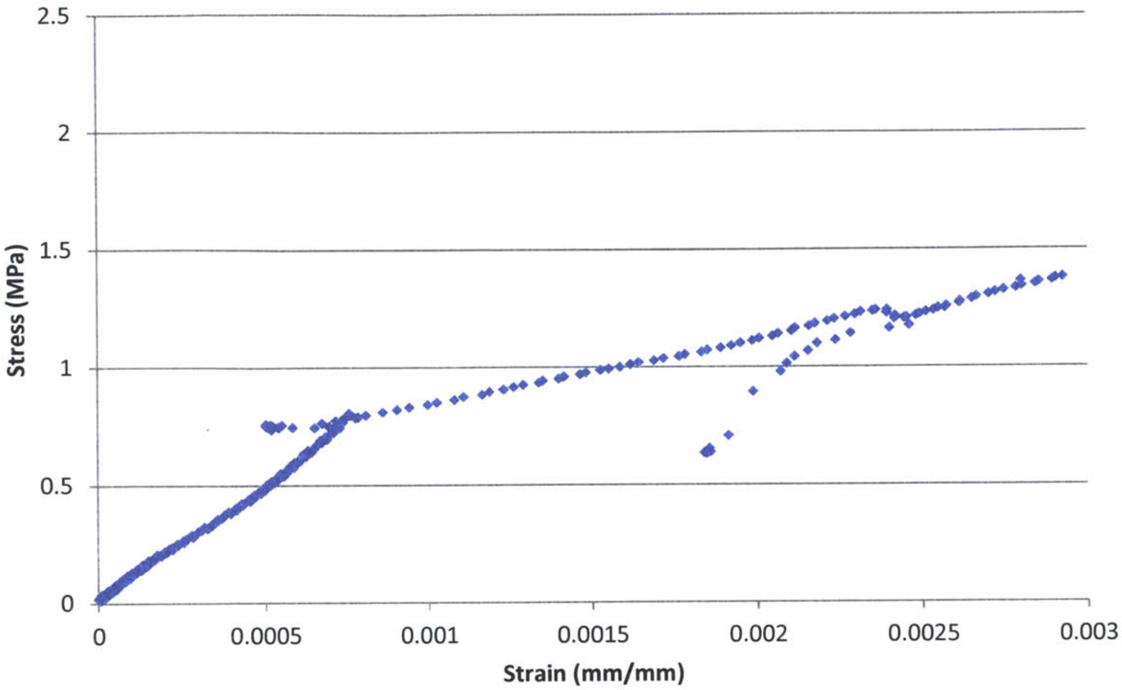

Figure 78: Stress vs. strain graph for the non-aggregate control cylinder, with a compressive strength of 1.38MPa and modulus of elasticity of 980MPa

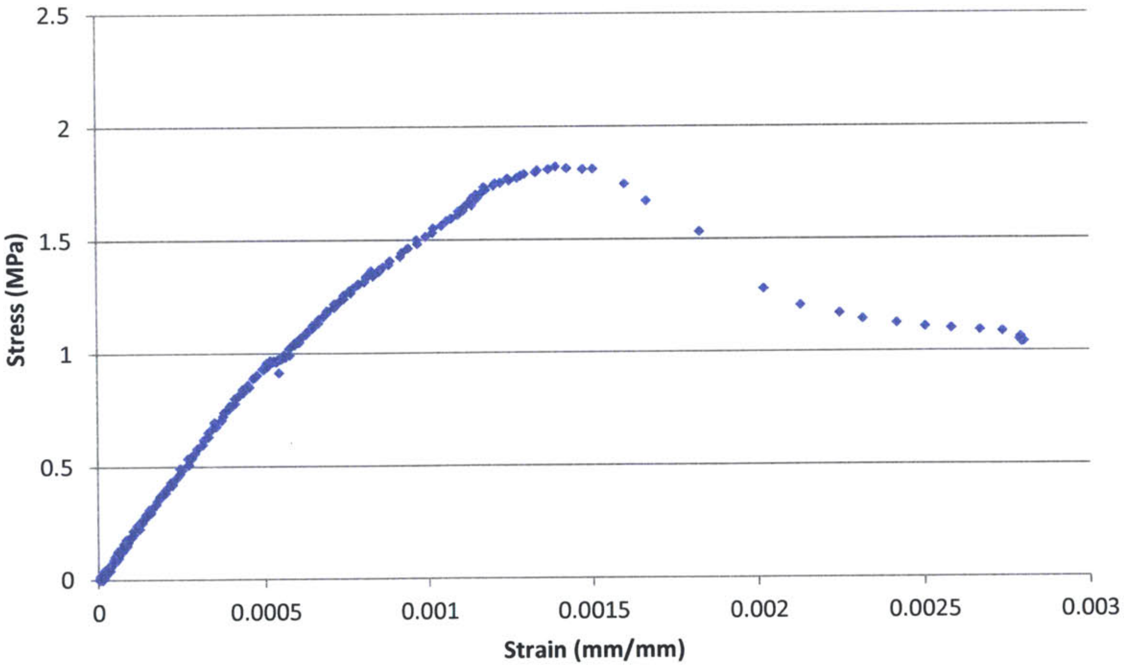

Figure 79: Stress vs. strain graph for the 0.187" aggregate cylinder, with a compressive strength of 1.82MPa and modulus of elasticity of 1940MPa

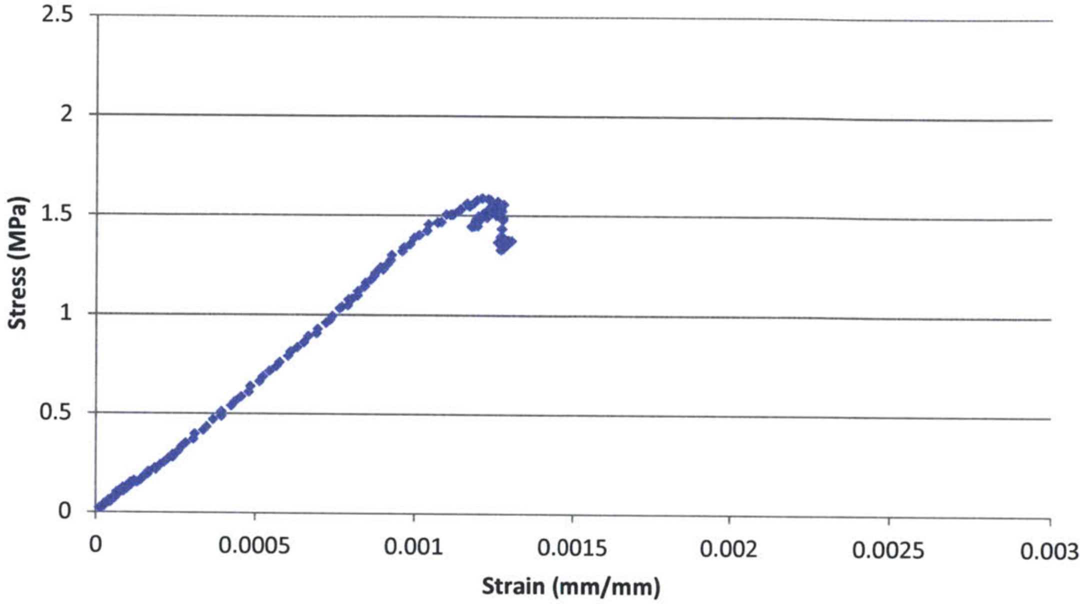

Figure 80: Stress vs. strain graph for the 0.25" aggregate cylinder, with a compressive strength of 1.59MPa and modulus of elasticity of 1370MPa

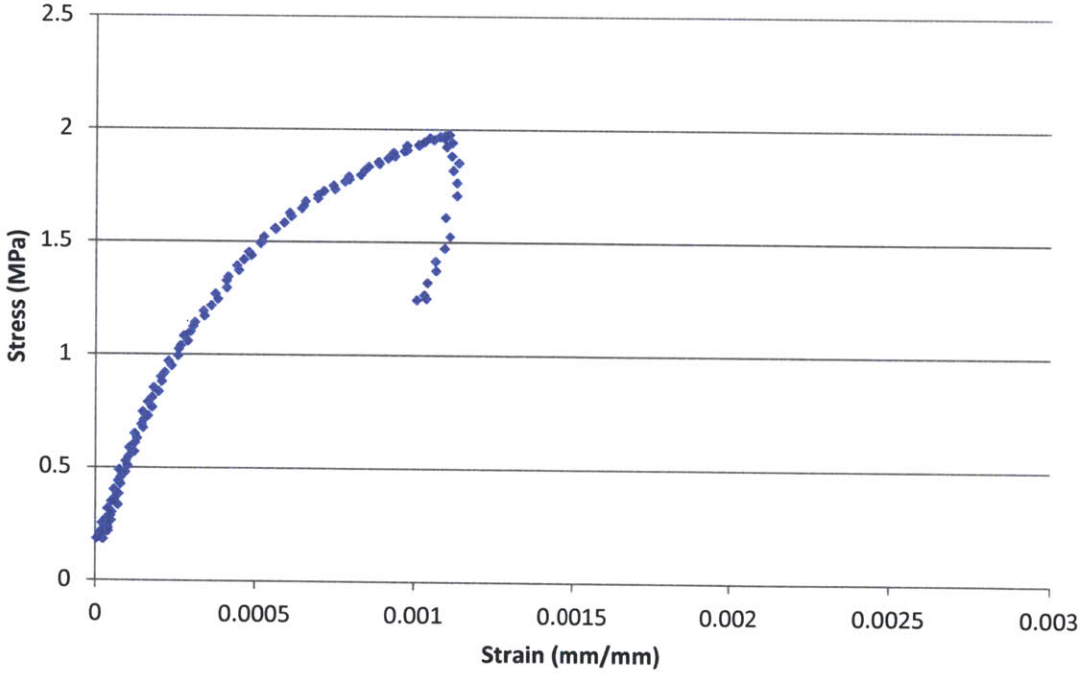

Figure 81: Figure 76: Stress vs. strain graph for the 0.371" aggregate cylinder, with a compressive strength of 1.98MPa and modulus of elasticity of 3350MPa

Appendix C: Materials and Equipment Supplier

Material/ Equipment	Supplier
Portland cement type I/II Quick Lime	*Waldo Bros.* 202 Southampton Street, Boston, MA 02118 Tel: (617) 445-3000 www.waldobros.com
Fly ash	*Headwaters Resources* Stephen Berlo, Technical Sales Representatvie 183 Turner Road, Scituate, MA 02066 Tel: (781) 307-6334 sberlo@headwaters.com
Technical aluminum paste	*SCHLENK-Both Metallic Pigments* Thomas Schaller, VP Sales and Marketing 40 Nickerson Road, Ashland, MA 01721 Tel: (508) 881-9147 ext. 331 www.schlenk.com
Fiber rope, plywood and miscellaneous equipment	*Home Depot* 5 Allstate Road, Boston, MA 02125 Tel: (617) 442-6110 homedepot.com
Fiber fabrics	*OnlineFabricStore* Tel: (877) 781-2967 onlinefabricstore.net info@onlinefabricstore.net
Plastic single-use cylinder molds (HM-151) and caps	*Gilson Company, Inc.* Tel: (740) 548-7298 P.O. Box 200, Lewis Center, Ohio 43035-200 globalgilson.com
Bandsaw (G0555 The Ultimate 14")	*Grizzly Industrial, Inc.* www.grizzly.com