ANALYSIS OF LOW-COST BUILDING MATERIAL

FOR THE MIXALCO PROCESS

A Thesis

by

L. CLINTON TITZMAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2006

Major Subject: Chemical Engineering

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Approved by:

Chair of Committee, Mark Holtzapple
Committee Members, Charles Glover
Cady Engler
Head of Department, N.K. Anand

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ABSTRACT

Analysis of Low-cost Building Material for the MixAlco Process. (December 2006)

L. Clinton Titzman, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Mark Holtzapple

The development of biofuels as an alternative fuel source highlights the MixAlco process as one method to convert organic waste into alcohol fuels. The pretreatment and fermentation of waste is integral to the process and represents a principal cost consideration due to the large structure needed to encapsulate the fermenting materials. This research developed papercrete as a potential construction material to reduce the cost of a structure. Papercrete is a mixture of paper, cement, and sand. The strengths, thermal conductivity, and other physical properties were compared with those of conventional building materials. This research identified acceptable property ranges necessary for using a structural papercrete facility and recorded compressive and tensile strengths that were too weak to build an economical structure. The identification of a hybrid papercrete-concrete structure produced results and economics within acceptable ranges. The papercrete-concrete alternative was tested on the same basis as the papercrete for structural and economic analysis, which provided acceptable results. The results indicate that a papercrete-concrete structure is a viable alternative structurally and economically within a range of sizes for the structure.

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CHAPTER I

INTRODUCTION

1.1 Background

The declining supply and rising price of oil is a growing concern worldwide. The search for alternative fuels is underway and many different energy sources are being explored. One very popular source of alternative energy is biofuels. Biofuels are being developed to bring the world a new fuel source. A process developed at Texas A&M University, called the MixAlco process (Figure 1), is one way to convert organic waste into alcohol fuels. An important part of the process is the pretreatment and fermentation of the organic materials.

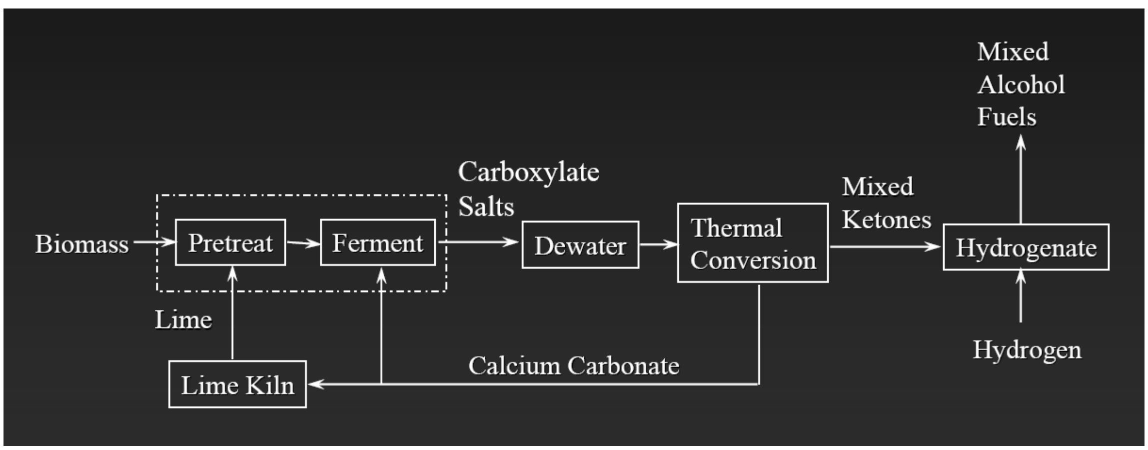

Fig. 1. MixAlco process (Holtzapple)

During this process, the organics are pretreated and fermented in large covered piles under ideal conditions.

This thesis follows the style and format of *Materials in Civil Engineering.*

For the MixAlco process to produce significant quantities to meet the nation's energy needs, the piles will require large encasement covering many acres of land. To make this process economical, the pile encasement must be constructed from a material that is relatively inexpensive, extremely durable, and completely waterproof. Papercrete, one alternative for constructing the encasement is investigated in this research to determine if it is viable as an option for maintaining the required conditions for pretreatment and fermentation piles. This research will compare papercrete to other engineered building materials to ascertain if it is more economical to use for large structures.

Papercrete is a mixture of cement, sand, and paper. When combined and cured, these materials produce a product similar to concrete; however, it is very lightweight. Furthermore, the cost efficiency gained by utilizing the ample supply of recycled paper reinforces the need for the research of this alternative. All portions of the encasement structure have different strength requirements. For example, the centerline of a beam does not need a large compressive strength. If we can reduce the construction material density by adding paper and use material in an efficient manner, we maintain a structurally sound building at a lower cost. It was decided to study papercrete to measure its strength, workability, and other properties to determine if it could be used to reduce the cost of buildings.

The quonset shape (Figure 2) was determined to be the building shape of choice. The arch structure is strong and durable, and the structure length could vary depending on size requirements. The strength and durability characteristics coupled with the size versatility make the quonset shape ideal for encasement requirements of the MixAlco process.

Fig. 2. Quonset shape

1.2 Research Goals

This research investigates different papercrete compositions that can be used to determine viability and efficiency by varying the compositions of the material mixes of cement, sand, paper, and water. These composition alternatives have varying associated costs and strengths; therefore this research will be used to choose an optimal mixture. Because the strength of the material is directly related to its density, the amount of papercrete that will be used for the structure varies with the composition. Therefore, an analysis of each composition will be used to determine if it is practical.

To determine if papercrete is a suitable building material for our needs, an approach for determining the physical properties is needed. The approach taken is similar to that of concrete. The papercrete studies were conducted as closely to the ASTM standards (American Concrete Institute 2004) for concrete as possible. Studies were performed to determine compressive, tensile, and flexural strengths of several different compositions of papercrete. The testing for the project was performed in the Structural Engineering Laboratory in the Department of Civil Engineering at Texas A&M University. The equipment used gave a precise stress analysis that includes the recording time, displacement, and force that was applied to the sample.

Compressive strength is needed to determine the wall thickness necessary to support the weight of the structure and external loads. The tensile strength of the material needs to be determined to counteract external loads on the structure. When the wind moves perpendicular to the quonset-shaped structure, it results in a negative pressure on the down-wind side, which will cause high tensile stresses on the structure. If these high tensile stresses are not mitigated, the structure will roll or possibly lift off the ground.

A safety factor was then applied to the final strengths, which will determine the maximum design stress that can be applied to the material before failure. These design stresses will set the limit at which the material can perform.

The measured strengths were implemented in a finite element analysis program to determine the necessary amounts of material needed for several sizes of structures. The five building size alternatives that were investigated are 20-, 50-, 100-, 200- and 400-feet wide quonset buildings. The cost per unit volume was determined for the various structure sizes. We can then determine an effective size of structure that can be constructed from papercrete, making the largest structure for the lowest cost.

After the size of the structure was determined, several construction techniques were analyzed and tested to determine feasibility and cost. Monolith and precast wall panel structures were explored to determine which is most efficient. The monolith structure consists of a structure formed in place, to the specified size. Then, the papercrete is poured or applied to the form, and cured in place. The forms are removed and the structure will stand completed. The wall panel structure will have precast panels that will be formed and cured in a factory. The wall panels will then be moved to their final location and assembled to make the building. Models will be constructed to help determine benefits and possible problems with each building technique.

These investigations will allow us to determine how papercrete compares to the cost of other materials. The comparisons will be used to determine if papercrete should be further investigated using a scaled building model for the pretreatment and fermentation processes.

CHAPTER II

LITERATURE REVIEW

The research was started when very little was known about the strength of papercrete. Several websites describe housing that was built from the material; however, most of the past research pertaining to papercrete was not conclusive regarding its strength and building properties. Several websites have since documented information on the properties of papercrete. The websites include information on compressive strength, and some thermal conductivity (Fuller 2004). There is no information available on the tensile or the flexural strength of papercrete. Several books have been published on the subject, mainly do-it-yourself manuals on how to make papercrete or how people have made low-cost houses from the material (Fuller 2004; Solberg 1999). These books discuss how to make mixers, basic mixes of papercrete, and other general construction techniques. This information has been used to explore building techniques and establish starting compositions of the papercrete mix. These resources have been used as guidelines to learn about papercrete, how to mix it, and some tests that will be useful to determine its properties.

2.1 Origin

Originally patented in 1928, papercrete was very difficult to market because it was so simple and inexpensive (Solberg 1999). After the original patent, the idea of papercrete remained dormant until the 1980's. Since this time, many people have used the material to build houses and other buildings. Because the owners of these houses do most of the work themselves, the cost estimates only include materials, not the cost of labor. These owners shared their knowledge allowing others to use the same techniques to build their own homes. As the knowledge was passed from one person to the next, many different methods were used creating various building techniques and ideas. Even the name of the material differs from one builder to the next, some calling it papercrete whereas others call it fibrous cement, or padobe. Papercrete has been used in several ways with a variety of techniques. Over the years, papercrete has changed considerably.

2.2 Previous Work

As previously stated, many people have used papercrete to build houses. Some information has been published on uses for papercrete, other information was found on how people made the material. However, there is a lack of information on the engineering properties of the material.

The only engineering properties that had been published on this material, when this research was started, were the compressive strength and thermal resistance. However, this information was not given for a particular mix of papercrete. So it was difficult to know what the composition of that mix was in order to verify the results.

The mixing methods and building techniques were thoroughly documented. Many different types of mixers have been used to make papercrete. These mixers ranged in size from 5 to 1500 gallons. For small batches of papercrete, a 5-gallon bucket, an electric drill, and a stucco mixer can be used. This method of mixing is very inexpensive, and is very effective for small batches. Some larger mixers use electric motors mounted to 55-gallon drums, with lawn mower blades used for impellers. However, the most unique mixer is a “tow mixer.” The “tow mixer” (Figure 3) uses a rear axle from an automobile to drive the impeller. The inventors removed the axle from the automobile, and turned the drive shaft to the vertical position. A hole was cut into the bottom of a livestock tank and the tank was mounted so that the drive shaft extended through the hole. Then the hole was sealed and a lawn mover blade was mounted on the drive shaft. A hitch was assembled to the axle, so the mixer could be pulled behind a truck. When the mixer is pulled behind the truck, the wheels turn the drive shaft which in turn moves the blade which mixes the papercrete. The “tow mixer” created an inexpensive way to mix large batches of papercrete. However, this invention is impractical for an industrial setting.

Fig. 3. Tow mixer (Fuller 2004)

The previously built structures have been constructed using several different building techniques. Many of the builders make papercrete bricks that vary in size, but are still easy to move by hand. These bricks are then assembled into the final structure by using papercrete as a mortar. This technique uses forms that are built to a specific size. Papercrete is then poured into these forms, allowed to set, and then the forms are removed. The papercrete is dried for several weeks before the bricks are assembled. This technique is similar to conventional brick houses, except the walls are load bearing. Other builders have used monolith structures that use forms constructed to the dimensions of the building. The form is then covered with the papercrete and allowed to set. When the papercrete is set, the forms are removed and papercrete supports the structure. This technique requires less labor, but the cost is high if the forms cannot be used again. The forms used for the bricks are reusable, but the monolith forms must be in place until the material is strong enough to support the load.

One of the most challenging problems with papercrete is its fluid retention property. When dry papercrete is exposed to water, the material acts like a sponge and absorbs the water. The moisture then reduces the strength of the papercrete; therefore, the papercrete must be sealed to stop water from penetrating the surface. Several different approaches have been used to stop the water from penetrating the papercrete. The first is to seal the papercrete with an elastomeric paint. This paint produces a thin, flexible rubber-like membrane when it dries. This technique has been reported to have a good record for holding up over long periods of time. However, the paint is very expensive. A less expensive alternative to the first approach is using roofing tar. The roofing tar will form an impenetrable barrier; however, the material can harden and crack due to sun exposure. If the cracks are not detected, the water can penetrate the papercrete and produce mold or mildew and degrade the papercrete. Another material that can be used to waterproof the papercrete is a crystalline waterproofing. The crystalline waterproofing material is a dry powder compound of Portland cement, very fine treated silica sand, and proprietary chemicals. This powder is mixed with water, and then applied to the surface that results in a reaction that forms non-soluble crystalline fibers within the pores and capillary tracts of the papercrete. “This compound is pricey, but said to be so effective that it is possible to make ponds with papercrete (Fuller 2004).”

These building details have been used to gain information to challenges that will be encountered when using the papercrete as a building material. These sources of information were used as starting points for the studies that are needed to approach papercrete from an engineering viewpoint.

CHAPTER III

PROBLEM STATEMENT AND CHALLENGES

3.1 Problem Statement

The pretreatment and fermentation steps of the MixAlco process require large covers to maintain ideal conditions in the piles. Large buildings are one technique that can create a barrier to maintain the conditions. To make the process efficient, the buildings must be constructed from a material that is inexpensive, but still sufficiently strong. Papercrete will be investigated to determine if it is sufficiently strong and less expensive than other building materials. This study will determine if papercrete can be built into the large structures needed for the MixAlco process.

3.2 Challenges

Papercrete has not been researched for commercial applications until now. Only houses have been made from papercrete; therefore, increasing the size of the buildings to cover the MixAlco piles is a challenge. The weather will play a role in this process. Papercrete loses strength when it absorbs water; therefore, it must be sealed to prevent moisture from reaching the papercrete. However, the papercrete cannot be coated with waterproof material while the papercrete is curing. To maximize its strength, papercrete needs to dry, as well as cure. Concrete sets during the first 24 hours after pouring; the hydration process occurs over many years. Concrete gains approximately 80% of its strength in the first 7 days of curing (Fintel 1985). If the concrete were wet for those 7 days, it would still gain the same strength. However, if papercrete were kept wet for 7 days, the strength of the material would not increase until the moisture was removed and the papercrete was allowed to dry. This means that the sealant for the papercrete cannot be applied until after the papercrete is fully dried. For small structures, this is not much of a concern because the small wall thickness takes less time to dry. However, when the walls on the structures increase in thickness, the drying time for the papercrete also increases. This will increase the construction time; therefore, weather plays a much larger role in industrial structures.

The papercrete can be constructed to withstand wind loads; however, the walls must be thick. This creates two problems. First, the amount of the material needed increases, which increases the overall cost. But more important, the drying time of the papercrete increases to the point where drying is difficult. Fluid transport through the wall slows as the wall becomes thicker; therefore, the walls will not be strong enough to support themselves for many months. This leaves a couple of options: (1) find a method to dry the walls quicker, which can be costly, and does not eliminate the problem with the amount of material used; or (2) reduce the amount of papercrete needed by adding a stronger material to the building.

CHAPTER IV

DESIGN BASIS

To determine the efficiency of building a large papercrete structure, the material properties of papercrete are required. The minimum strength of papercrete is necessary for the structural analysis of the building. The prototype building would be located in Bryan, Texas. The minimum design loads for that location will help determine if the strength of the material is great enough to be used for the pile buildings.

4.1 Wind Load

The most critical load on the prototype for Bryan, Texas is wind. According to the ASCE standard, a 100-mph wind load is specified for Bryan, Texas (Engineers 2003). The shape of the quonset building presents several problems for determining the loads and pressure distributions on the building. The ASCE standards do not present information for wind pressures on the quonset shape. The pressure distributions in the standards only include buildings with vertical walls. Wind tunnel testing is the required procedure for determining the pressures on the quonset shape. A study was found for wind tunnel pressure distributions on the quonset shape (Chien et al. 1951). The information from the study made it possible to determine the forces present on the structure at different wind speeds.

The pressure exerted at different locations of the structure makes it possible to develop a force diagram (Figure 4). Because the pressure profile changes as the wind flows over the arch, different forces are applied to the surface of the arch to determine the maximum stress that will be applied to the building in the 100-mph wind.

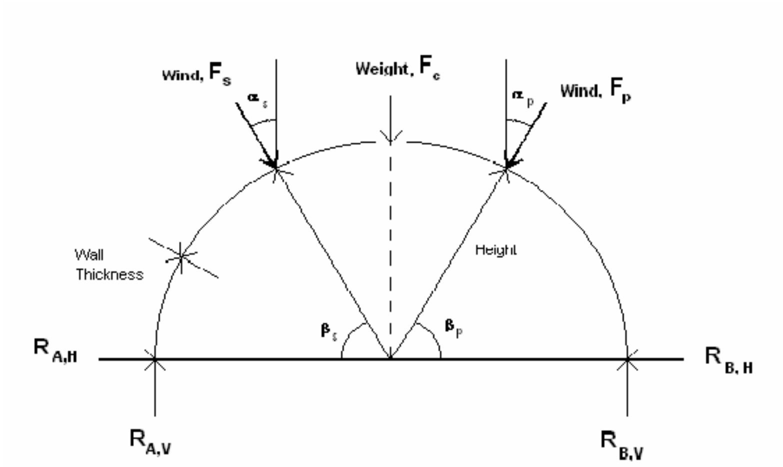

Fig. 4. Force diagram

The wind forces on the structure were greatest when the direction of the wind was perpendicular to the longest side of the arch. A combined wind profile, which shows the maximum forces on the arch, is shown in Figure 5. It was necessary to combine several wind angles to determine the maximum possible stress on the arch.

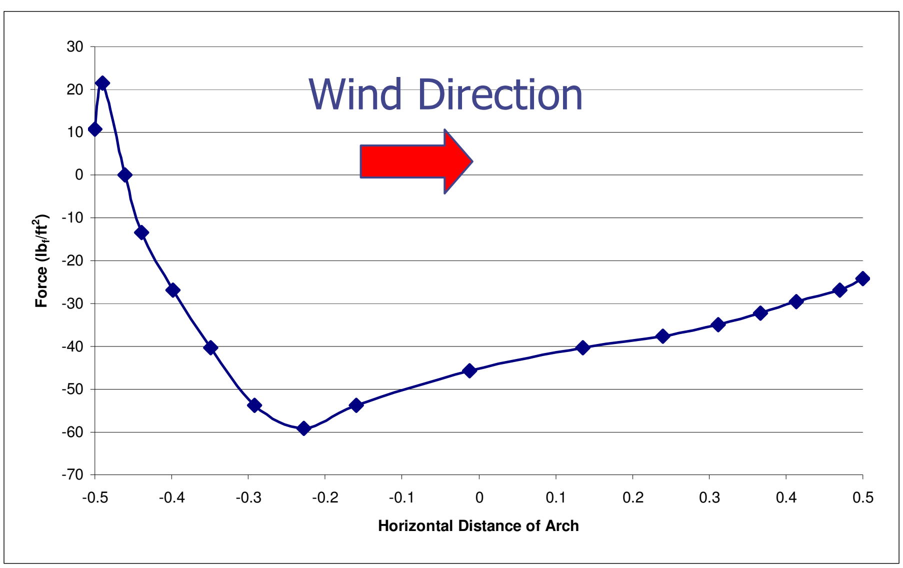

Fig. 5. Wind profile of quonset hut

As illustrated in Figure 5, most of the wind pressure on the arch is a vacuum. The arched structure acts as an airfoil, which can cause the building to roll if proper footings are not installed. For purposes of this structural analysis, the base of the walls is assumed to be properly secured.

The snow load and rain load on the structure were irrelevant, due to the location of the building, and the shape of the roof, respectively. As stated previously, this analysis of loads only included supporting the building weight and environmental loads. This preliminary analysis was to determine if papercrete would be economical if used for the building structure. Any additional loads would most likely result in an increase in wall thickness.

4.2 Dead Load

The dead load of the building is a stress factor on the building that is constantly present. According to the ASCE Standards definition, "the dead loads consist of the weight of all materials of construction incorporated into the building including but not limited to walls, floors, roofs, ceilings, stairways, built-in partitions, finishes, cladding, and other similarly incorporated architectural and structural items, and fixed service equipment including weights of cranes." (Engineers 2003)

The dead load, according to this definition, will be the weight of the walls. This depends on the final thickness of the walls, which will be determined by the final strength of the material. Finite element simulation will be used to calculate the dead load. To determine the dead load on the building the density of the materials used must be determined in the testing phase of the study.

4.3 Safety Factor

The safety factor of the building is determined by several considerations. An important consideration is the nature of occupancy. Because this building will be used as an agriculture warehouse, it is classified at the lowest importance. "In concrete structures, the overall factor of safety may range between 1.56 and 1.82" (Calderone 2002). Because the importance of the building is considered to be low, the safety factor of this building will be taken to be 1.56. Therefore, the nominal strength of the papercrete will be equal to the tested strength divided by 1.56.

CHAPTER V

METHODOLOGY

5.1 Introduction

Written engineering standards do not exist for testing papercrete; therefore, concrete standards were used as guidelines for the testing. Several different tests were conducted to determine the strength of the new material. To perform these tests accurately, the test samples must be made in a uniform fashion. These samples were then used to test the compressive, tensile, and flexural strengths. These tests formed a basis for which a final composition was determined. More tests were then performed on the final composition to learn more about papercrete. This approach helped to minimize the cost of testing. Bonding and thermal resistance were additional tests performed. Bonding helped determine how other materials bond to the papercrete and thermal resistance determined the insulation value of the papercrete. This section will cover all of the procedures used to make and test the samples.

5.2 Preparing Samples

When preparing the samples, it is very important for each batch and individual sample to be made consistently. This reduces the error caused by bad sampling. The accuracy of the samples for the compressive, tensile, and flexural tests greatly depends upon how the samples are made. Some of the initial samples that were made varied greatly due to density variations caused by sample preparation.

To make and cure the compressive or splitting tensile strength specimens, cylinder molds were used. These cylinders, according to ASTM standards, must be at least 3 times the maximum size of the aggregate (American Society of Testing and Materials 2000). In the case of papercrete, because the paper fibers are very small, 4-inch-diameter cylinders were used. The length of the cylinder is twice the diameter; therefore, the length is 8 inches. The 4 x 8 inch cylinder is a common sample size for small aggregate concrete. These samples were set and cured in the upright position to satisfy the ASTM standard.

After the size of the mold was established, a procedure for molding was determined. Tamping the papercrete was determined to be the best way to make a consistent sample due to the thickness of the material. A 0.75-inch and a 2-inch tamping rod were used to pack the papercrete into the mold. The 0.75-inch rod has a rounded end that was used to tamp the papercrete. The larger tamping rod was a pipe that had a 2-inch-diameter head.

The procedure for producing the sample, once the papercrete was made, started with placing enough papercrete into the mold so that it was approximately one third full. Then, taking the 0.75-inch tamping rod, the material was tamped 25 times by hand penetrating the papercrete throughout its depth, distributing the tamping over the entire surface evenly. After the initial tamping, the 2- inch tamping rod was used to tamp the material 15 times, evenly distributing the tamps across the papercrete. When tamping with the 2-inch rod, the papercrete was penetrated only about ½ inch. After tamping the papercrete, the sides of the mold were tapped by hand 10 to 15 times to help release any air voids. More papercrete was added to fill the mold to approximately two-thirds full. The tamping was repeated with the 0.75-inch rod, penetrating the bottom layer approximately 1 inch. Then the tamping was repeated with the 2-inch rod as performed before. The sides of the mold were tapped by hand 10 to 15 times to release the air voids. The mold was filled with additional papercrete until the mold overfilled. The tamping process was repeated, as previously stated. The 0.75-inch rod was used to roll the spare papercrete off the top of the mold and smooth the papercrete to the rim of the mold. This procedure was used each time a cylinder mold was made making a consistent practice for making test specimens.

The beams used for flexural strength testing were 12 inches long, 2 inches wide, and 2 inches tall. The beam dimensions were set according to ASTM standards for concrete flexural strength testing. These beams were poured, set, and cured horizontally. Papercrete was poured into the beam mold until it was above the rim. The 0.75-inch tamping rod was used to tamp the material into the mold 30 times to evenly distribute the length of the form. The side of the mold was then tapped by hand 10 to 15 times to release the trapped air in the mold. A trowel was then used to level and remove excess papercrete from the form leaving a smooth top surface of papercrete.

The cylinder and beam samples were left in the molds to set for 24 hours. After this time period, the samples were removed from the forms. These samples were then placed in the same position that they were poured. The next step in the process was to cure and dry the samples. Because cement hydration occurs over a long time period, the samples needed to stay moist for the hydration reaction to go to completion. The natural drying time of the papercrete varies with various mixtures. The curing of the cement and the drying process of the papercrete occurs simultaneously. In most cases, the drying time was longer than the 28-day curing process. The samples were then tested after drying was complete. The drying period was complete when the sample weight stabilized. Drying time results can be found in the appendix. The test samples were kept in an air-conditioned building during the curing process, which might have decreased the drying time from an outdoor location, where the humidity changes frequently.

5.3 Density

The density of the papercrete was measured after the samples were completely dry. This would reflect the conditions that the papercrete would need to perform when the structure was erected.

To determine the density, the samples were weighed on a daily basis to determine when they were completely dry. When the samples maintained a constant weight, the drying process was completed and the density was then calculated by dividing the weight of the sample by its volume. Once the density of the dry papercrete was determined, the weight of the structure could be calculated.

5.4 Compressive Strength

The compressive strength of papercrete needs to be determined for the structural analysis of the pile cover. The compressive strength can be used to judge the overall strength of papercrete. The equipment needed to test the compressive strength is located in the Structural Engineering Laboratory in the Department of Civil Engineering at Texas A&M University. Computer-controlled static actuators provide the compressive loads needed for the testing. Every 2 seconds the system records the compressive force applied and the displacement of the test sample. These data provide the stress-strain curve needed to determine the failure point of each sample. The papercrete compression tests were all performed using the same procedures.

5.4.1 Procedures

To determine the compressive strength of the material, a cylinder measuring 8 inches tall and 4 inches in diameter was placed in the actuator (Figure 6). The actuator was set to load the sample at 20 pounds per second.

Fig. 6. Cylinder compression test

The test was started by applying a force to the cylinder. When papercrete compresses, the material has vertical displacement (Figure 7) and then fractures (Figure 8).

Fig. 7. Cylinder displacement

Fig. 8. Cylinder fracture

The time of testing varied according to the strength of the sample. The force and displacement was automatically recorded every 2 seconds. The actuator was set to constantly increase the load every second; therefore, the displacement varied as the force was applied. The test was stopped when the sample became fractured, as shown in Figure 9. When concrete is compressed, the vertical displacement is minimal, and when it fails, it has an abrupt fracture (Hassoun 2002). In contrast, when papercrete is compressed, the material has more displacement and then slowly fractures.

5.4.2 Analysis

After the data were recorded, an analysis was used to determine the exact failure point. The initial deformation in the sample is called elastic deformation. Elastic deformation is non-permanent, which means that when the applied load is released, the piece returns to its original shape. The elastic deformation region of the stress-strain curve is linear. The failure point is determined when the force causes non-recoverable or permanent deformation called plastic deformation (Figure 9). The plastic deformation region of the stress strain curve is the non-linear region.

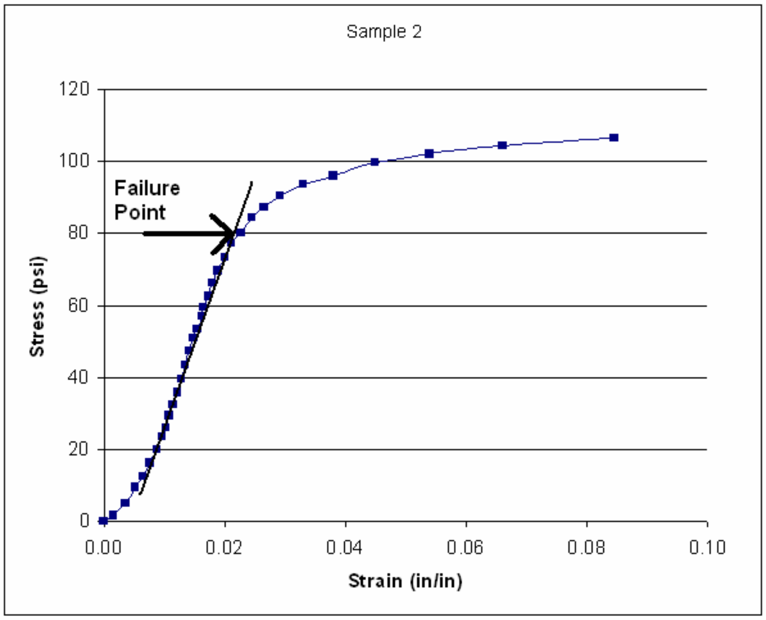

Fig. 9. Compressive test stress-strain curve

The force applied every second to the sample is divided by the surface area to give the stress at each data point. The original length divided into the displacement of the sample gives the strain. The stress and strain at each point are then plotted giving the stress-strain curve. The failure point is then determined from the stress-strain curve. Because papercrete was considered a linear material, the failure point was found when the stress was no longer proportional to the strain. When the stress-strain curve became non-linear, the failure point was reached. In some cases papercrete is a non-linear material. However, by treating it as a linear material, the test time was reduced. The determined papercrete strength from non-linear testing would be greater than the linear and the difference between the two test methods would be minimal, so the linear approach was taken to be conservative.

Engineering Stress (Callister 2001): $\sigma = \frac{F}{A_o}$

Engineering Strain (Callister 2001): $\varepsilon = \frac{l_i - l_o}{l_o}$

$F =$ Instantaneous load (lb_f)

$A_o =$ Original cross-sectional area (in^2)

$l_i =$ Instantaneous length (in)

$l_o =$ Original length (in)

The sample shown in Figure 10 shows the compressive strength to be 81 pounds per square inch. End effects cause the initial non-linear section of the stress-strain curve, which is caused by irregularities in the ends of the papercrete. The modulus of elasticity is also calculated from the stress-strain curve. The modulus of elasticity is equal to the slope of the linear section of the stress-strain curve. This property will be needed for the structural analysis. This analysis was repeated for all papercrete samples that were tested. The results of these tests are in Section 5.3.

5.5 Tensile Strength

A cylinder-splitting test was used to determine the tensile strength of the papercrete. The same size cylinder is used for the tensile test as was used for the compression test. The same data and equipment were used to determine the tensile strength that were used for the compressive strength.

5.5.1 Procedure

To determine the tensile strength of the material, a cylinder was placed in the actuator horizontally (Figure10). The actuator was set to load the sample at 10 pounds per second.

Fig. 10. Split cylinder tensile test

To start the test, a force was applied to the cylinder. When papercrete was compressed, the material had vertical displacement and fractures (Figure 11). The force and displacement were automatically recorded every 2 seconds. The test was stopped when the sample fractured, as shown in Figure 11.

Fig. 11. Tensile test fracture

5.5.2 Analysis

The same stress-strain analysis was used for the tensile test. The main difference is how the stress is calculated. Because a compressive force was used to determine the tensile strength, the following equation was used to relate the two:

$$T = \frac{2P}{\pi DL}$$

where:

T = splitting tensile strength (lb_f/in^2)

P = maximum applied load indicated by the testing machine (lb_f)

L = length (in)

D = diameter (in)

The splitting tensile strength will be determined by the stress-strain curve. A sample stress-strain curve for the tensile test is shown in Figure 12. For this sample, the tensile strength was taken to be 25.6 psi. The same elastic deformation region and plastic deformation region is shown in the graph. This analysis was repeated for all papercrete samples that were tested.

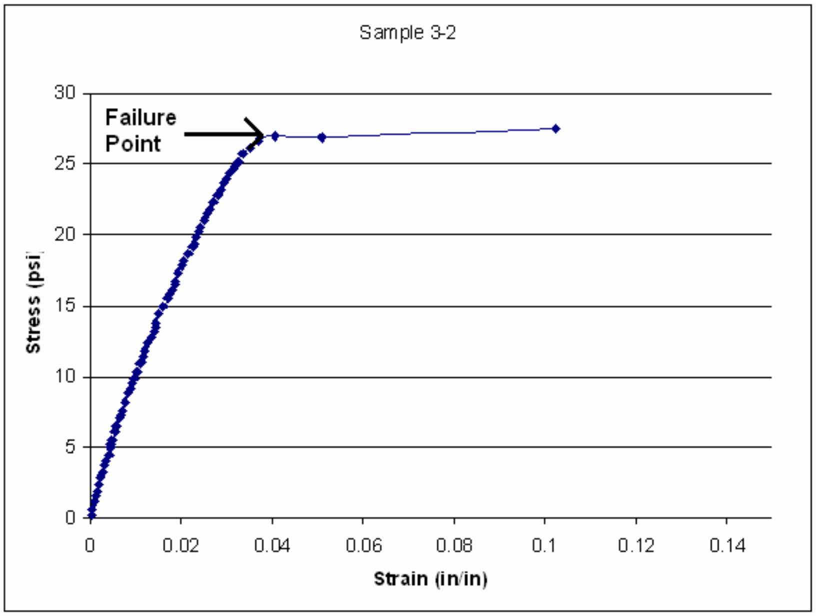

Fig. 12. Tensile stress-strain curve

5.6 Flexural Strength

The flexural strength of the papercrete is needed for the structural analysis as well. To determine the flexural strength, a center-point loading method was used. This method uses the same actuator used in the previous test. However, another attachment is needed to perform the test. The attachment supports a 2x2x8 inch papercrete beam at the ends. The top attachment places a load on the center of the beam. When the test was started, the load increased at 2 pounds per second. The force is applied as shown in Figure 13.

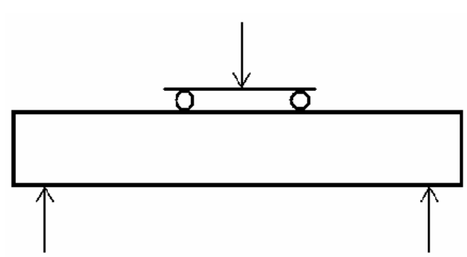

Fig. 13. Center-point loading method

After the force was applied, the papercrete did not deflect visibly before the fracture occurred. The break was sudden, and each sample broke in the middle third of the sample. The purpose of the center-point loading flexural test (Figure 14) was to break the beam at the weakest part in the middle third of the beam.

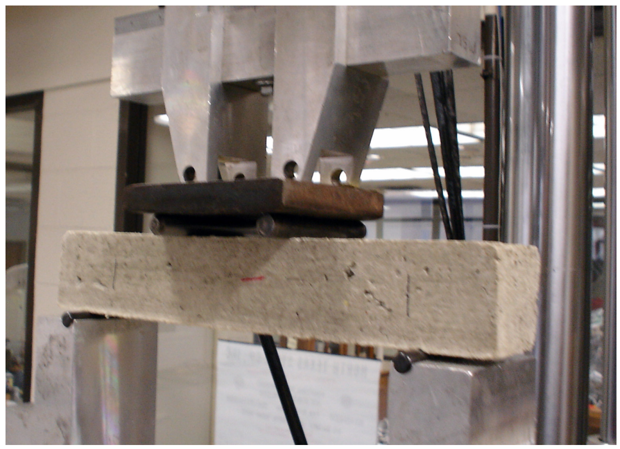

Fig. 14. Center-point flexural strength test

The maximum force applied to the beam was used to determine the flexural strength. This force was used to calculate the modulus of rupture. The width and depth of the beam at the fracture area was also needed for the calculation. The following equation is used to calculate the modulus of rupture:

$$R = \frac{PL}{bd^2}$$

where:

$R =$ Modulus of rupture (lb_f/in^2)
$P =$ Maximum applied load indicated by the testing machine (lb_f)
$L =$ Length of span (in)
$b =$ Average width of specimen at fracture (in)
$d =$ Average depth of specimen at fracture (in)

This equation is valid for all breaks that occur in the middle third of the beam. The results of the testing are shown in Section 6.3.

5.7 Thermal Conductivity

The thermal conductivity is not needed for the structural analysis of the pile cover; however, it is needed to determine insulation properties. Because of the conditions that must be maintained inside the pile, the insulating properties value of the papercrete can save energy costs. To measure the thermal conductivity a cylinder approximately 4 feet long, with an 8- inch outside diameter and a 4-inch inside diameter, was made from the papercrete (Figure 15).

Fig. 15. Thermal conductivity test

Light bulbs were evenly spaced inside the cylinder that provided heat from the inside. Thermometers were placed on the inside and outside of the cylinder to determine the temperatures. The ends of the cylinder were then sealed with fiberglass insulation. The light bulbs were turned on, and the temperatures inside and outside were allowed to reach steady state, which took approximately 8 hours (Figure 16). The steady state temperatures were then recorded.

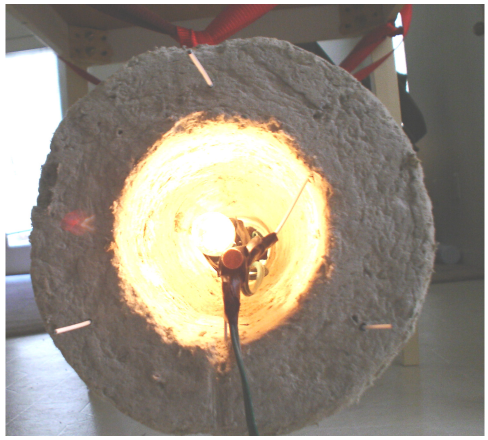

Fig. 16. Light bulbs inside cylinder

Knowing the power from the light bulbs, the cylinder dimensions, and the temperatures inside and outside of the cylinder, the thermal conductivity of the papercrete was calculated using the following equation (Incropera and Dewitt 2002):

:

$$k = \frac{q_r \ln \frac{r_2}{r_1}}{2\pi L(T_{s,1} - T_{s,2})}$$

where

$k =$ thermal conductivity (W/(m·K))

$q_r =$ wattage of the bulbs (W)

$L =$ length of cylinder (m)

$T_{s,1} =$ Inner cylinder temp (K)

$T_{s,2} =$ Outer cylinder temp (K)

$r_1 =$ Inner radius (m)

$r_2 =$ outer radius (m)

This procedure was used to calculate the insulation value of the papercrete. By knowing the insulation value, the heat lost from the pretreatment and fermentation piles can be determined.

5.8 Flammability

The flammability of papercrete was briefly tested to determine if it would be fuel in the event of a fire. A flame was applied to a papercrete sample. The flame was applied and the papercrete did not ignite. The papercrete started to smolder; however, it never ignited. When the flame was removed from the papercrete there were visible marks where the flame was applied, but it self extinguished; therefore, papercrete is not a flammable material.

CHAPTER VI

PAPERCRETE TESTING

6.1 Composition

The composition of the papercrete used for the structure is one of the most important parts of the research. To determine if large structures can be constructed from papercrete, the material properties must be determined. Therefore, seven different compositions of papercrete were tested to determine the compressive and tensile strengths of each. This narrowed the number of compositions from seven to one. This one composition was then researched further to determine the modulus of rupture, modulus of elasticity, and Poisson's ratio.

The mixtures of papercrete tested (Figure 17) used different compositions of paper, sand, and cement. The amount of water used for the mixture varied to keep the mixture at a consistent viscosity to ensure proper mixing.

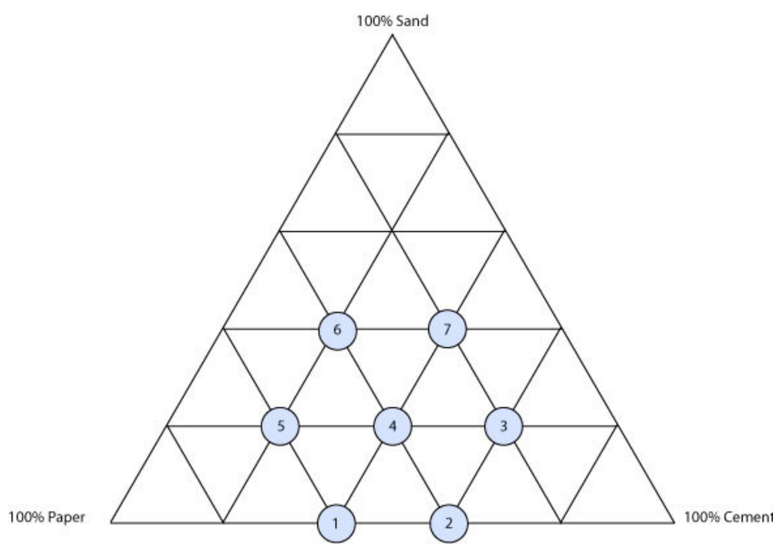

Fig. 17. Composition of papercrete batches

These papercrete samples were tested to determine the compressive and tensile strengths. The results of the testing are shown below. The compositions were then eliminated for different reasons until one was left. Compositions 2, 4, 5, and 6 were eliminated because they were very soft after the 48-hour setting time. These compositions would be very difficult to handle for several days, and their tensile strengths would not support the wind loads. Compositions 1 and 7 were eliminated because of their low tensile strength, which is needed to withstand the 100-mph wind. The cost analysis showed that the highest strength composition was not significantly higher than the weaker compositions. The cost of the strongest batch of papercrete was approximately $\$0.95/ft^3$. This cost was based on the price of cement, sand, and recycled newspaper in May 2006 (See Table 1). To put this price in perspective, a building that is 20 feet wide, 53 feet long, and has a 6-inch thick wall will cost approximately $1600 for materials.

Table 1. Cost of Materials (U.S. Geological Survey January, 2006), (Central Texas Recycling Association 2006), (All American Stone and Turf 2006)

Recycled Newspaper	$70/ton
Cement	$90/ton
Sand	$\$22/yd^3$

6.2 Optimization of Composition

Several different compositions of papercrete were tested to determine their physical properties. The paper, cement, and sand percentages were varied in the mixture. Seven compositions were tested to determine the compressive strength. The exact compositions were chosen to create a variety of strengths, which would allow us to determine the most economical and practical mixture to be used for the building.

The concrete provided bonding between the paper fibers; therefore, more concrete added increases the strength more than the other two components. However, concrete was more expensive than paper and sand; therefore, cost was directly related to strength. The paper was used as a lightweight “filler” material that increased the volume, therefore making the building material less expensive. The more paper used, the weaker the papercrete. Sand increased the strength of the material during the setting period. Papercrete with a higher concentration of sand was more stable after the setting period. This made handling the “wet” papercrete less difficult, because the papercrete with the higher concentration of sand had more strength upon setting. The sand is also believed to reduce the amount of shrinkage that occurred in the samples. The reduction of shrinkage would reduce the tendency to crack upon drying.

The amount of water in the compositions played an important role in the strength. This phenomenon will be discussed further in Section 5.5. More water was needed to pulp the paper than was needed in the hydration reaction; however, excess water weakened the papercrete. This meant that any additional water reduced the strength of the papercrete; however, the volume increased, which reduced the cost. Excess water in the mix also meant that the papercrete needed more time to dry after the setting period. The papercrete became stronger as it dried. The papercrete needed to be completely dry to increase the strength to a maximum. Initially, water was added and mixed to maintain a similar viscosity throughout the various compositions. The amount of water was then increased to make mixing the papercrete less difficult. After testing the samples, it was determined that the water content of the papercrete was very significant. It might be beneficial to mix the papercrete with higher water content and then drain the water out of the mix to increase the strength of the papercrete, while still making it less viscous during mixing. The results from different compositions are shown in the next several sections.

CHAPTER VII

COMPRESSIVE AND TENSILE STRENGTHS

7.1 Results

The compressive strength of the papercrete had a large variance depending on the composition tested. Results of the compressive testing are shown in Figure 18.

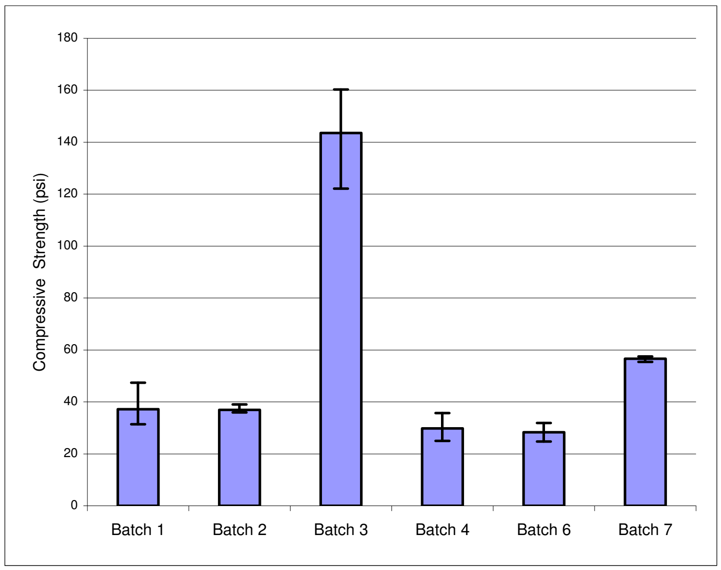

Fig. 18. Compressive strengths of various batches

Figure 18 shows that compressive strength varies widely with composition. The compressive strength for the initial test was taken from three samples and then averaged. The maximum and minimum compressive strength of the papercrete was 143.6 and 28.3 psi, respectively. The standard deviation of the samples are shown in Table 2.

Table 2. Compressive Strength Standard Deviation

	Compressive Strength Standard Deviation (psi)
Batch 1-1	8.8
Batch 2-1	1.8
Batch 3-1	19.5
Batch 4-1	5.4
Batch 6-1	3.5
Batch 7-1	1

The results of the initial tensile strengths are shown in Figure 19. The strengths were determined with the same method as used for the compressive tests.

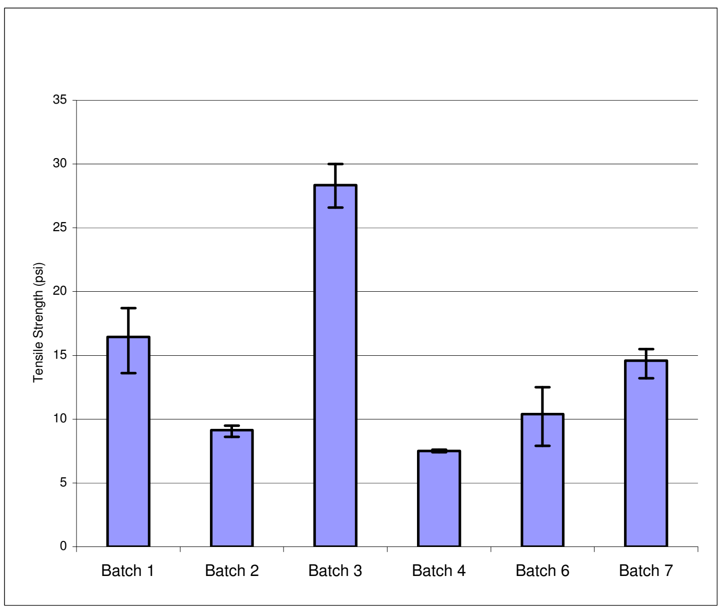

Fig. 19. Tensile strength

The maximum and minimum tensile strength of the papercrete is 28.3 and 7.5 psi, respectively. The tensile strength was also taken from three samples. The tensile strength standard deviations are shown in Table 3. The compressive strength of papercrete is an important factor of the strength; however, for determining the optimal composition of papercrete the most important property is the tensile strength. The tensile strength of the papercrete was determined to be the limiting strength. The tensile strength is needed to overcome the external wind load. The wind force on the building will be counteracted by the tensile strength of the papercrete. If the tensile strength of the papercrete is too low, the wall thickness must be increased to withstand the wind.

Table 3. Tensile Strength Standard Deviation

	Tensile Strength Standard Deviation (psi)
Batch 1-1	2.6
Batch 2-1	0.5
Batch 3-1	2.4
Batch 4-1	0.2
Batch 6-1	2.3
Batch 7-1	1.2

7.2 Density

The calculated densities are shown in Figure 20, which shows that the density of the material increased when the percentage of cement in the mixture increased. When the amount of paper in the mixture increased, the density decreased. Comparing the results of the density and compressive strengths, the more-dense papercrete was stronger than the less-dense material thus compressive strength was a function of density (Figure 21).

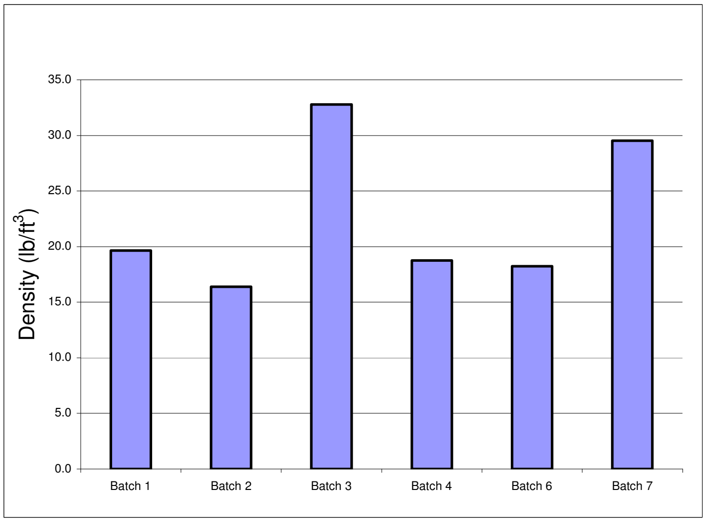

Fig. 20. Density

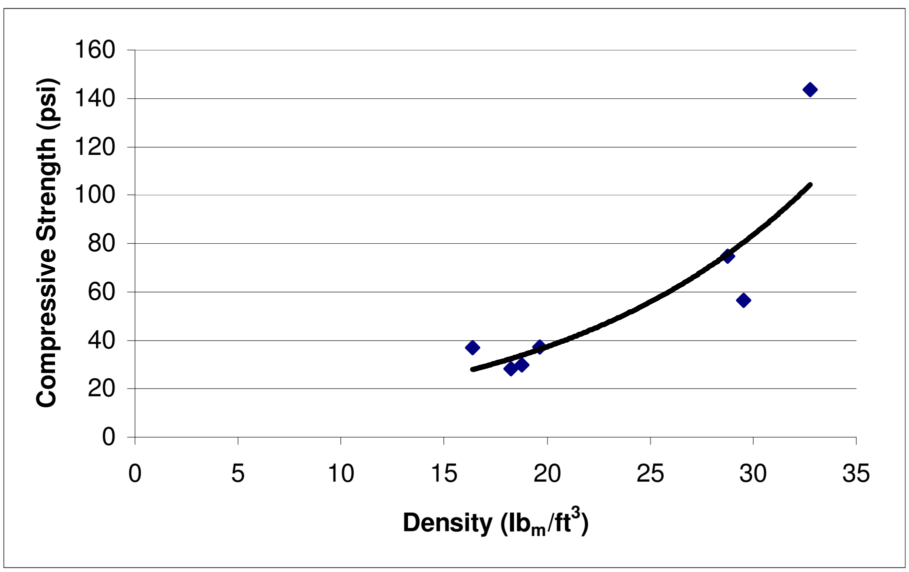

Fig. 21. Compressive strength versus density

7.3 Final Composition

The properties of papercrete are crucial to determine which composition is most efficient for constructing a quonset building. Besides the strength and density of the papercrete, the cost, shrinkage, and several other properties were estimated to determine the most efficient composition. The ideal papercrete properties would have high compressive and tensile strengths, low shrinkage, and a low cost (Figure 22). Most of the compositions tested can be eliminated from this description due to their low strength. The strength of one composition stands above the others. Batch 3 has a higher strength and lower shrinkage than the other compositions.

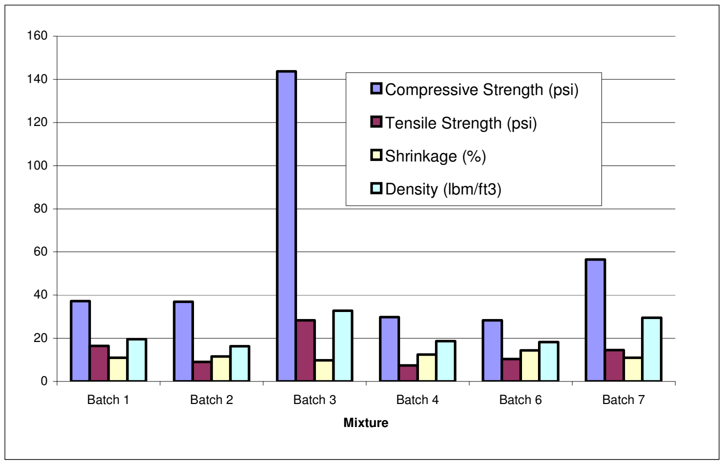

Fig. 22. Papercrete properties

However, due to its high percentage of cement in the papercrete, the cost of Batch 3 (Figure 23) is higher than the costs of the other compositions. The cost of the papercrete is a major factor in determining if the material is viable for use as a building material.

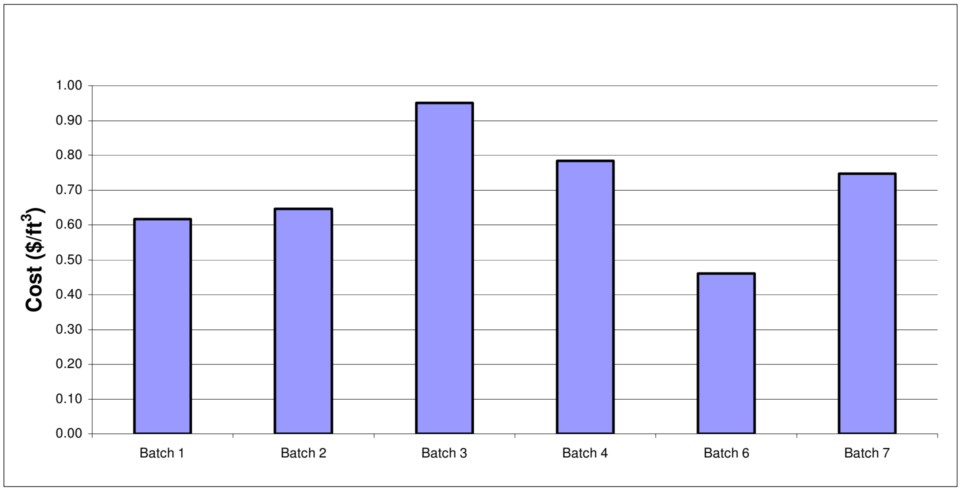

Fig. 23. Cost of papercrete

It was determined that although Batch 3 was more expensive, per unit volume, the overall cost would be reduced because the walls would be thinner. The cost (dollars per cubic foot of material) includes only the cost of paper, cement, and sand. This does not consider the strength of the material, which means that more volume of a weaker material is needed to create a structurally sound building. Therefore, it was determined that the composition of Batch 3 would be used for the quonset structure.

The composition of Batch 3 is 20 wt% paper, 60 wt% cement, and 20 wt% sand. The water content was varied in the initial batches to create various viscosities of the wet mix. It was difficult to determine how much water content affected the strength of the papercrete, but it definitely affected the density. The initial water mixed into Batch 3 was 11.5 mL/g paper. To determine the affect of the water on the mixture, it was increased 20% to 13.8 mL/g paper. The effects of the increase are shown in Figure 24.

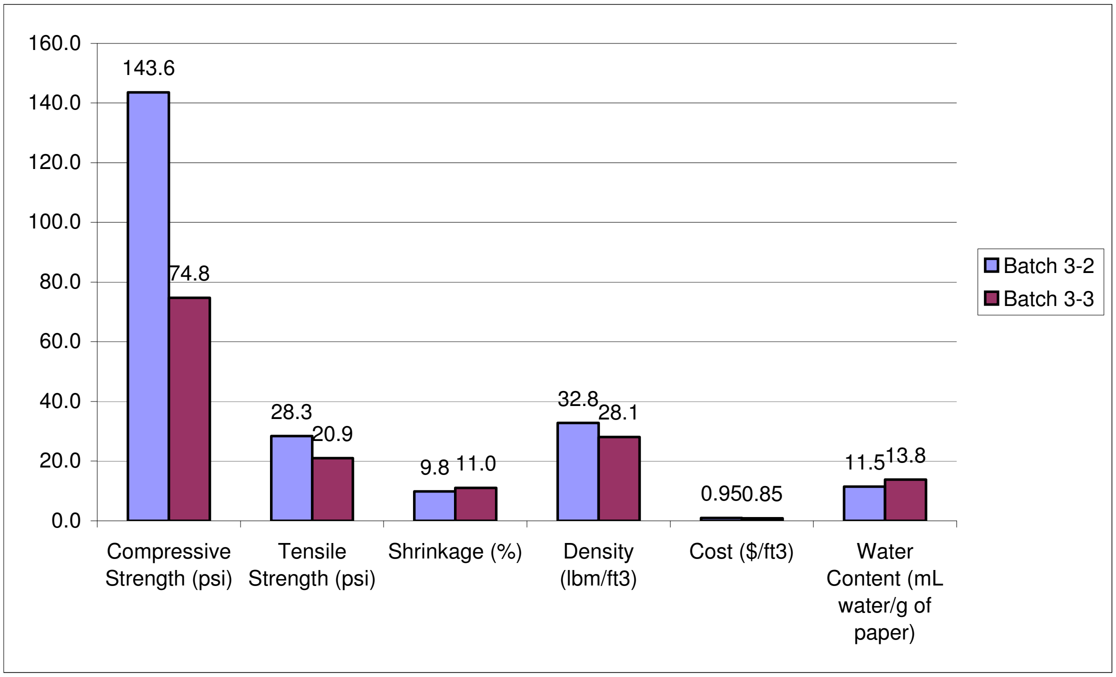

Fig. 24. Effect of water

The 20% increase in water dramatically reduced the compressive strength from 143.6 to 74.8 psi, or 48%. The tensile strength of the papercrete reduced from 28.3 to 20.9 psi, or 26%. The shrinkage increased slightly by approximately 1.2%. The density reduced by 14%, and the cost was reduced by approximately $0.10/ft^3$. The main benefit of the increased water was the ease of mixing. Because large batches of papercrete will be required to construct a building, higher water content will be necessary for mixing. The papercrete must be mixed with the exact amount of water or the strength of the papercrete will vary dramatically.

The final composition that was used for thorough testing was a mixture of 20 wt % paper, 60 wt% cement, and 20 wt% sand. The amount of water that was added was 13.8 mL/g paper. This composition will give the strongest papercrete that can be easily mixed with a large batch mixer. This high water content reduced the compressive strength dramatically and the tensile strength modestly. The tensile strength is the more important feature for resisting wind loads.

Tensile and compressive strengths were already determined through the initial screening. Further investigation measured the modulus of rupture, modulus of elasticity, and Poisson's ratio, which were needed for the finite element analysis. The modulus of rupture was determined to be 62 psi, the modulus of elasticity was 3580 psi, and Poisson's ratio was 0.0141. The modulus of rupture and Poisson's ratio were estimated from compressive strength testing.

7.4 Thermal Conductivity

The thermal conductivity of the papercrete was tested to determine its insulation value. After the lights were turned on inside of the cylinder, it took approximately 7 hours for the temperatures to reach equilibrium. The lights were left on for several more hours to ensure the temperatures stayed constant. A temperature distribution (Table 4) across the cylinder was caused by papercrete porosity. The cylinder was poured in the upright position; therefore, the weight of the papercrete made the bottom portion of the cylinder more dense than the top.

Table 4. Thermal Conductivity Testing

	More Dense						Less Dense
Outside Temperature	Port 1	Port 2	Port 3	Port 4	Port 5	Port 6	Port 7
27 °C	97 °C	101 °C	103 °C	104 °C	104 °C	105 °C	106 °C

The cylinder was made 4 feet long so that end effects would have minimal effects on the temperatures. The temperature in the middle section was constant showing that the temperature loss from the ends did not affect the calculations. The testing shows that the density of the papercrete affects the thermal conductivity. The temperature increased the most near the thermometer ports where the density of the cylinder was the lowest. The density effect was observed from the porosity of the material. A comparison for effect of density on the thermal conductivity was not thoroughly analyzed; these were merely observations to explain the testing results.

The reported thermal conductivity for the papercrete was based on the middle section of the cylinder. The thermal conductivity was 0.10 W/(m·K) (0.06 Btu/(ft·h·°F)). Concrete has a thermal conductivity between 1.25 and 1.75 W/(m·K). Papercrete has a much lower thermal conductivity than concrete; therefore, its insulation value is much higher. The papercrete thermal conductivity is similar to several other materials (Table 5).

Table 5. Thermal Conductivity of Selected Materials (Callister 2001)

Material	**kW/(m·K)**
Fiberglass Insulation	0.038
Papercrete	**0.1**
Polyvinyl Acetate Cork	0.1
Plywood	0.12
Concrete	1.25

Table 5 shows that papercrete has great insulating value. Although papercrete must be approximately 2.5 times thicker than fiberglass insulation to provide the same thermal resistance, concrete must be 12.5 times thicker than papercrete to provide the same thermal resistance. Papercrete is a very good insulating material.

CHAPTER VIII
STRUCTURAL ANALYSIS

8.1 Papercrete Arch

A structural analysis is needed to determine if a building can be constructed from papercrete. This analysis will also give cost estimates for the material needed to construct the building. The structural analysis was performed with a finite element program (Algor). The analysis was used to determine the stress and strain of the structure when a wind force is applied. This allows the maximum stress to be determined on the material before failure occurs so that the material strength can be specified.

The finite element analysis allows the geometry of the walls to be varied so it is possible to determine how much material is needed to construct a building that meets building codes. The papercrete modulus of elasticity, modulus of rupture, Poisson's ratio, and density were entered into the material properties of the finite analysis. The finite element analysis then gives the stress and the strain that occur on the structure under a 100-mph wind load.

The first size structure that was analyzed was an arch with a 20-foot diameter. The arch was made 1 foot deep to determine the amount of material needed per foot of arch. The initial 20-foot diameter arch had 4-inch-thick walls (Figure 25). The wind pressure was then applied to the arch to determine if the maximum allowable stress was exceeded. The base of the arch was secured in the simulation, which meant the maximum stress would occur in the papercrete. This assumption was made on all of the simulations. The assumption is validated in the Chapter IX.

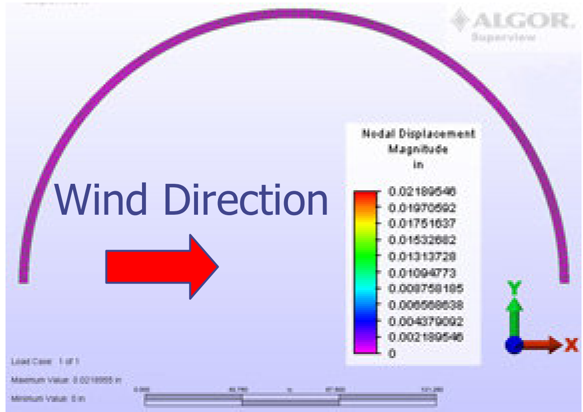

Fig. 25. Papercrete arch simulation model

The initial run of the arch with 4-inch wall gave a maximum tensile stress of 74 psi. For papercrete, the maximum allowed tensile stress is 13.5 psi, after the safety factor is applied. The maximum tensile stress occurred at the outer surface of the wall. Therefore, the wall thickness must be increased to lower the tensile stress; however, to lower the maximum tensile stress to 13.5 psi, the wall thickness must be increased to approximately 15 inches at the base. The drying time would increase to several months, which presents a challenge for passive air drying. Active heating would be required.

To reduce the wall thickness, a new approach was taken. Because the maximum stress occurred at the outer layer of the material, a stronger layer could be placed on the outside of the papercrete that would provide sufficient strength (Figure 26).

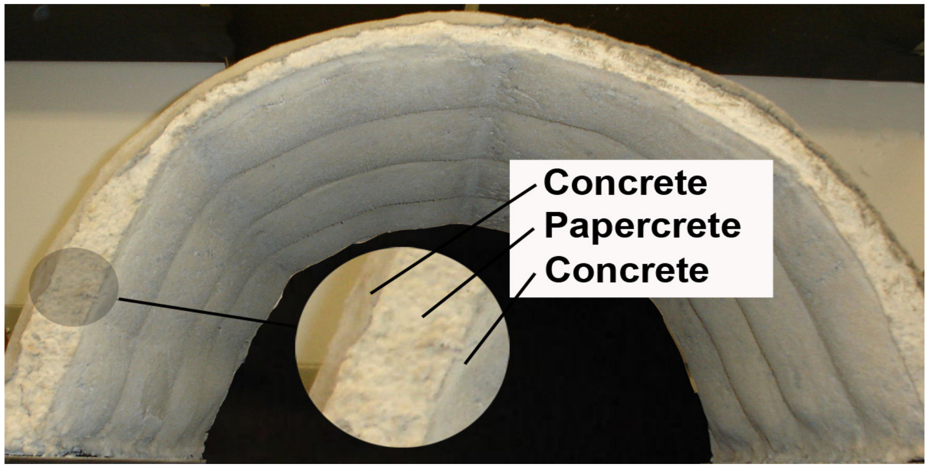

Fig. 26. Layered arch

Concrete was then tested to determine its physical properties so that it could be applied in thin layers to the papercrete. This would reduce the wall thickness on the arch, because only the area near the surface of the arch required the high strength. Because a higher strength material would be on the surface, the stress could be higher and still maintain a structurally sound building. It was determined that the center of the wall would have the lowest stress; therefore, the papercrete would be used as a filler to separate the stronger material. The cost of the building would be reduced because the portion of the wall, bearing the lower stress, would be made from the less expensive material.

8.2 Concrete Testing

A determination was made that papercrete alone would not create the most efficient building structure; therefore, concrete would be added as an additional layer to provide additional strength. If a thin layer of concrete could be added to the papercrete structure, then the amount of material could be reduced to make the building more economical. Several important tests would be required to determine if a concrete layer could be added to the papercrete to increase the overall strength. First, the strength of concrete mixtures would need to be determined. Second, the concrete would need to be layered on the papercrete to determine if they would bond properly so the layers would perform properly when placed under stress. Finally, a process for layering the papercrete with concrete would need to be established.

To determine the dimensions of the structure required to withstand the minimum design requirements of a 100-mph wind, the compressive, and tensile strength of concrete needed to be analyzed. The concrete analysis would be performed according to ASTM standards. Concrete has been a well-researched material for many years; however, the best way to determine the strength is to perform the tests using the same materials and mixtures that are being utilized in the structure. This eliminates the error associated with variance of the materials used. The coarse aggregate strength plays an important role in the physical properties of the mixture. If the aggregate is not the same as the original structure, then the strengths will vary. Testing the different mixtures will also allow us to determine the densities and the costs more effectively.

Riverbed pea gravel was used as the coarse aggregate in the concrete mixtures. The size of the pea gravel allows the surface of the building to remain smooth. The smooth surface would reduce water penetration into the concrete. Water traveling through concrete causes several problems, such as impurities that lead to premature degradation. The concrete will also be used as a sealant to protect the papercrete; therefore, water penetration needs to be minimized to prolong the life of the structure.

Several compositions were tested to determine which would be most efficient. All of the compositions were tested with and without nylon fibers. Nylon fibers have been known to increase the tensile strength of concrete, and because additional tensile strength is required, the nylon option was explored. Table 6 shows the list of concrete compositions that were tested.

Table 6. Tested Concrete Mix Volume Ratio

	Concrete	*Aggregate	Sand
Batch A	1.5	1	3
Batch B	1	1	2
Batch C	2	1	3
*Pea gravel			

Masonry mortar was also tested as a stucco layer to provide the needed additional strength for the structure. Masonry mortars Type N and Type S were mixed and tested with and without nylon fibers. Nylon was also explored in the stucco layer in the same manner as the concrete. The nylon was added to each batch at a suggested ratio of 5 ounces per cubic foot of concrete. If the nylon effectively increased the strength of the concrete, then other ratios could be explored to find an optimal amount needed to maximize strength. These different mixtures were tested to explore which layer could be used with papercrete to create the most economical building.

The compressive, tensile, and flexural testing revealed which mixture was the strongest and had the minimal cost. The averages of the three tested samples for tensile and compressive strength are shown in Table 7.

Table 7. Concrete and Mortar Strengths

Without Nylon:	**Compressive (psi)**	**Std. Deviation**	**Tensile (psi)**	**Std. Deviation**
Batch A	5340	342	447	30.4
Batch B	6085	385	495	43.9
Batch C	4109	171	398	27.1
Type S	1440	100	252	4.3
Type N	2090	498	214	35.4
With Nylon:				
Batch A	5456	53	339	12.7
Batch B	7769	242	456	71.2
Batch C	3470	68	296	14.0
Type S	1493	86	193	7.1
Type N	1613	496	240	7.0

In most cases, nylon actually decreased the tensile strength. The compressive strength was increased in several of the mixtures; however, the compressive strength is not our limiting factor. The option for using nylon was then eliminated. Therefore, the decision is based on the highest tensile strength with the lowest cost. Table 8 shows Batch B is the lowest cost and it has the highest strength.

Table 8. Concrete/Mortar Cost

	Cost ($\$/ft^3$)
Batch A	2.76
Batch B	2.68
Batch C	3.04
Type S	6.11
Type N	6.12

The final properties of Batch B are shown in Table 9. These properties will determine the thickness of the stucco layer. The finite element analysis will be used to estimate the amount of concrete and papercrete needed to construct the quonset building.

Table 9. Batch B Properties

Batch B	
Cost ($\$/ft^3$)	2.76
Compressive Strength (psi)	6,085
Tensile Strength (psi)	495
Modulus of Rupture (psi)	729
Density (lb_m/ ft^3)	144
Poisson's Ratio	0.2
Modulus of Elasticity (psi)	4,400,000

8.3 Layered Quonset Analysis

Now that the strength of the concrete is known, the finite element analysis of the structure can be completed. Concrete will be added to both the inside and outside of the papercrete. Concrete is the strongest, yet most expensive material in the structure. To create a cost-effective structure, a minimal amount of concrete must be used.

The layers were created in the finite analysis program and the force of a 100-mph wind was applied. A trial-and-error process was used to reduce the tensile stress on the concrete to be below 390 psi. A safety factor of 1.56 was applied to the tensile strength to over-design the building. The over-design will account for any flaws in assembly, material degradation, and uncertainty of loads.

After several iterations, the stress was below the concrete strength everywhere except where the concrete meets the footing. Figure 27 shows the maximum tensile stress for the arch.

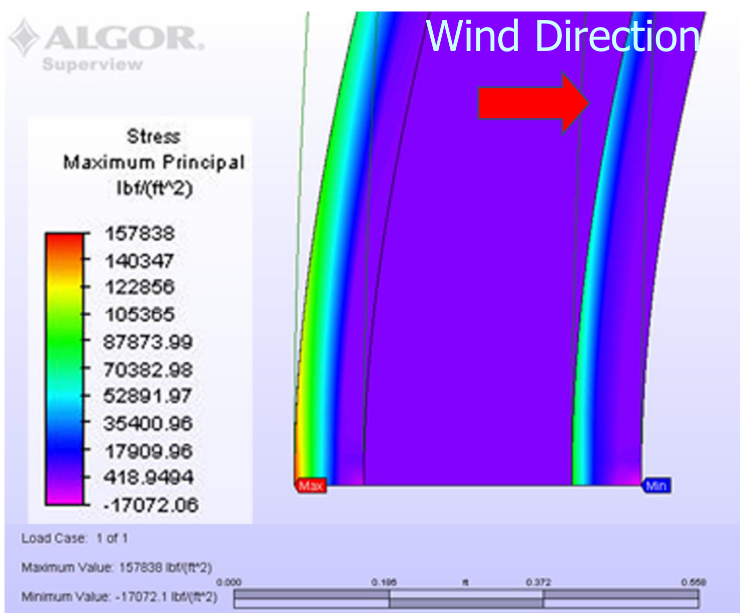

Fig. 27. 20-ft diameter arch maximum tensile stress

This 20-foot arch has a 3-inch papercrete center covered by one inch of concrete on the inside and outside of the wall. The maximum tensile stress occurs at the base of the arch. To reduce the stress at the base, a fillet was added to the bottom of the arch on both the inside and the outside (Figure 28).

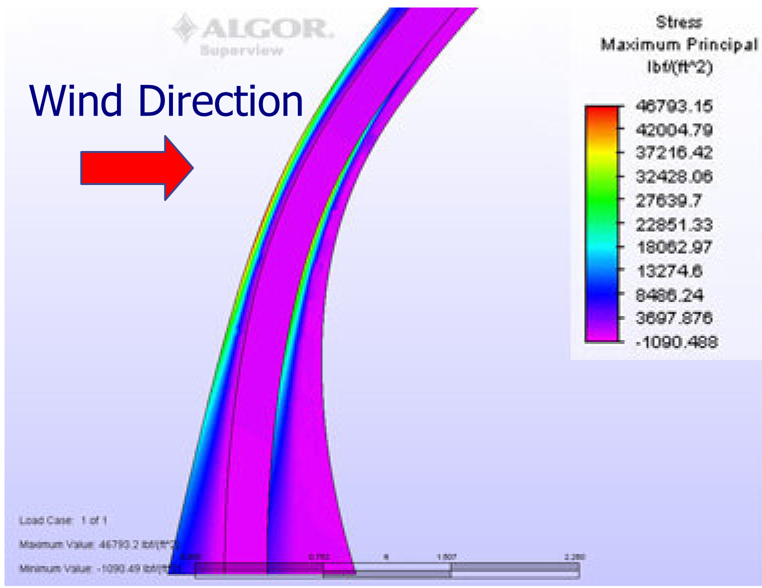

Fig. 28. 20-ft diameter arch with 3-inch inner and outer fillets

By adding the 3-inch fillets, the tensile stress was reduced below the maximum stress requirements for the concrete. The cost was kept at a minimum because concrete was added only in the required location.

The structural analysis also showed the deflection of the building in the 100-mph wind (Figure 29). The deflection is exaggerated to show the deflected shape. The maximum displacement of the material is approximately 0.9 inches.

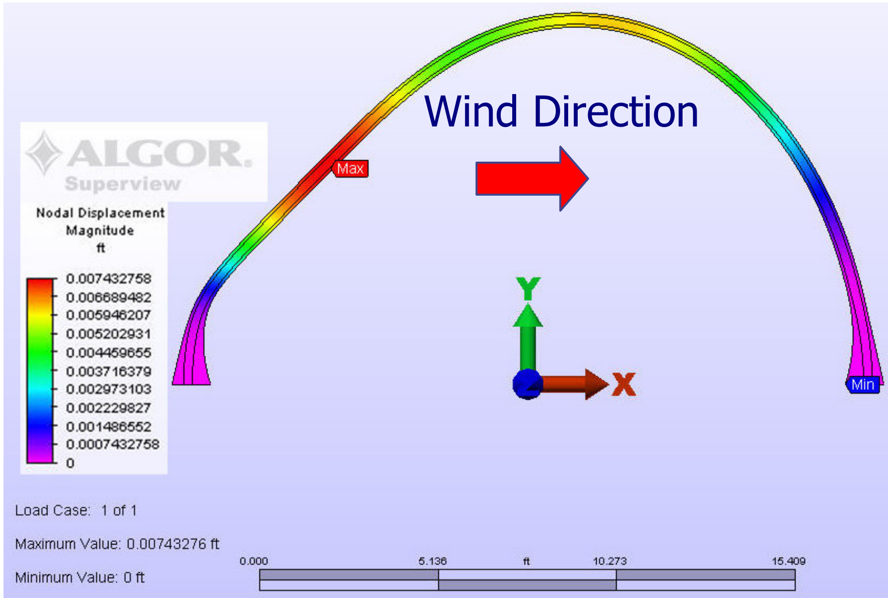

Fig. 29. 20-ft diameter arch maximum displacement.

The results indicated that a 3-inch papercrete center could be covered by a 1-inch layer of Batch B concrete and withstand a 100-mph wind if the bottom of the wall had 3-inch fillets to secure the building to the footing. The additional width at the base would reduce the stress of the wall below the maximum tensile strength.

The cost of the building was analyzed per foot of arch. Buildings could be constructed at varying lengths without significantly increasing the cost. Per foot of 20-ft-diameter arch, the volume of papercrete would be approximately 6.22 ft^3 and the volume of concrete would be 13.57 ft^3. This analysis shows that it would cost about $54 per foot of arch for the building materials. For a building 50-feet in length, the total cost of concrete and papercrete would be about $2700, or $0.14 per square foot. However, the cost per square foot is misleading. Because the piles will be built to use the vertical space as well as the floor space, the cost per cubic foot of interior volume is the more important parameter. The papercrete/concrete designed quonset hut will be compared to steel structures as an alternative structure. The cost per cubic foot will also allow us to determine which diameter building minimizes the cost of storage space for the pile. The cost per cubic foot for a 20-foot arch is about $0.38. If the structure were made completely from concrete the cost per cubic foot would be about $0.46; therefore, the papercrete reduced the material cost about 20%.

The finite element analysis was also performed on arches with 50-, 100- 200-, and 400-foot diameters. These additional diameters will provide a cost per volume that will allow us to determine the optimal size structure. The optimal size will provide a structure that can hold the pile at the most economical price. This cost is compared to standard current building materials in the cost analysis section.

CHAPTER IX

BUILDING TECHNIQUES

9.1 Introduction

Several building techniques were researched to determine which would be the most feasible and cost effective. Monolith and precast wall panel structures were the methods of choice. The wall panel structure uses precast panels, formed and cured in a factory, then moved and assembled at a final location. Using this approach, most of the critical processing steps can be performed in a controlled atmosphere inside a factory. In contrast, the monolith structure uses a preshaped form, to which papercrete is applied in the field. Once the papercrete sets, the forms will be removed leaving the structure standing in its final location.

9.2 Precast Wall Panel Building

When the wall panel process begins, the papercrete will be mixed in large batches that can be poured into reusable prefabricated forms (Figure 30). These forms can be built into any shape and size that allows the process to be customized. “The forms are vitally important in precast panel work and the type depends on considerations of cost, maintenance, reuse, and detail. Concrete wood and steel forms are quite common” (American Concrete Institute 1965). The prototype form was constructed from wood, which is less durable but costs less than steel.

Fig. 30. Papercrete in wall panel form

The papercrete was allowed to set before the molds were removed, which minimized panel damage. Larger panels have more volume; therefore, they required a longer setting time to insure they had the proper strength before being removed from the molds. Prototype panels were formed and removed after varying amounts of time. This determined the setting time needed to prevent damage to the panels upon removing the forms. After the panels were removed from the molds, they were allowed to dry in a controlled environment. The drying process occurs more quickly in a low humidity atmosphere, which would allow a quicker production time. To determine the length of time that the panels needed to dry, the weights were recorded. When the weight became stable, the drying process was complete. A dried panel is shown in Figure 31. After the drying process, the panels can be sealed with a waterproof coating and transported to the final location for construction.

Fig. 31. Dried wall panel

At this point, the panels must be assembled to construct the building. The bottom panel must be secured to the footing that will restrict it from moving both horizontally and vertically. The panel can be secured using angle iron (Figure 32) that will run down the length of the arch along the base. Figure 32 shows the holes in the angle iron along the base of the building.

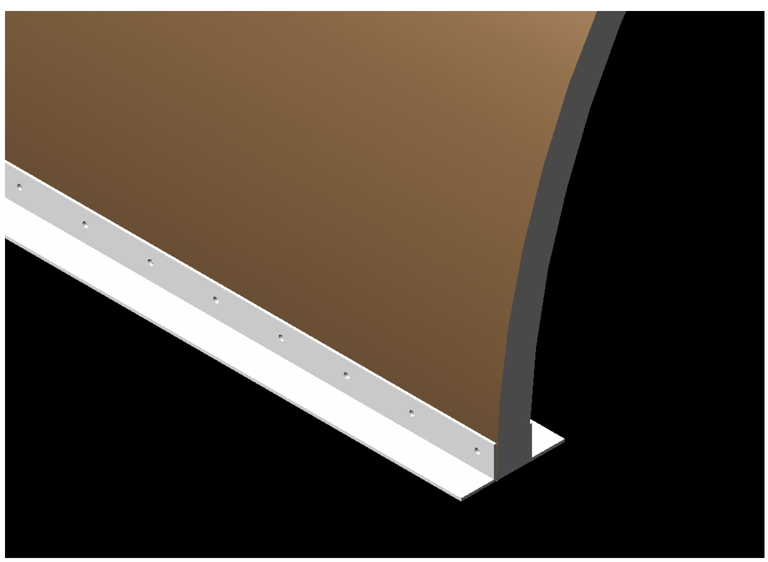

Fig. 32. Angle iron on footing

Bolts can be used to secure the papercrete to the angle iron, which is attached to the foundation. If the stress concentrations on the papercrete are too great for the papercrete the footing could be bonded to the papercrete with glue or mortar. This would distribute the stress throughout the papercrete, preventing the maximum stress from being exceeded. This method for securing the arch to the footing validates the previous assumption that the base of the arch is stationary (Chapter VIII). For the walls to be assembled, removable forms need to be constructed to support the structure while the mortar sets. Testing showed that masonry mortar bonds well to papercrete and costs less than other bonding agents. The structure can be built from the ground upward, using forms to support the papercrete (Figure 33). After the mortar sets, the forms are removed and the joints between the panels are sealed to prevent water from penetrating the papercrete.

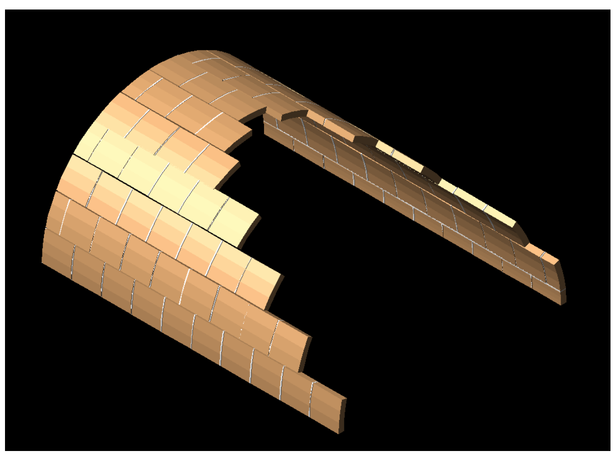

Fig. 33. Precast wall panel construction

This method has several advantages that make it a viable option. First, the panels can be constructed in an environment that prevents rain from slowing down the drying process. Second, the material is not subjected to the loads of the structure until after the drying process is complete. This reduces over-design, because the loads are not applied to the material while in a weak state. When the panels are sealed in the factory, the ends can be sealed as well, preventing water leakage from panel to panel should the sealant be penetrated. Each panel becomes an individual unit that is impermeable to water; therefore, if water penetrates the seal, only one panel has a loss of strength.

Disadvantages to using this method include labor cost. Because the bricks are precast and assembled, the time of construction is increased causing higher labor costs. The overall cost of the building will increase, reducing the possibility of being cost effective.

9.3 Monolith Building

The cost of labor of the precast wall panel structure provided a basis for further research in another building technique. The monolith structure was researched to determine if it was feasible. The monolith allows the structure to be made at the final location and in one major step.

The building will initially take shape using a large form. In an ideal situation, the form is easily constructed and disassembled. This form is only a temporary part of the building. A model was used to determine what materials could be used for the forms. Initially a shell (Figure 34) is formed using strong materials that will support the weight of the wet papercrete.

Fig. 34. Monolith shell

The model quonset shape shell had a diameter of 2-feet and was constructed from 3/8-inch rebar, which was welded together, and wire-tied across the rebar to form the semi-circular shape. The shell was then covered with a fine-mesh window screen (Figure 35) which held the papercrete on the form. The small holes in the window screen allowed the water to penetrate the papercrete and dry from both the inside and outside of the structure. The main purpose of the window screen was to support the papercrete, while drying, to give the structure its final shape.

Fig. 35. Model monolith form

The window screen was then covered with a poultry netting that had approximately 1-inch diameters holes. The papercrete was pushed through the poultry netting to prevent the papercrete from running down the sides of the form. Figure 36 shows the papercrete after it had been applied to the form.

Fig. 36. Papercrete applied to monolith form

This experiment determined that the papercrete could be applied easily to a form, and will set quick enough to hold a desired shape. A form that is designed to support the load of the wet papercrete can be used to form the papercrete into the final shape of the building. One problem that occurred with the model form was that the window screen deflected (Figure 37) on the inside due to inadequate support.

Fig. 37. Window screen sag

To prevent reoccurrence of this problem, the screen will need to be supported in short intervals. A wire that had 6 x 8 inch rectangular voids supported the screen. The papercrete was applied to the screen approximately 2 inches thick. Poultry netting can be stretched across the wire, and then applied to the screen to eliminate the deflection in the screen. After the papercrete dries, the form can then be removed (Figure 38) leaving the self-supporting papercrete in place.

Fig. 38. Papercrete quonset hut

A scaled-up version of this form will probably consist of steel pipe, rebar, poultry netting and a steel window screen. Initial costs may be high; however, the form is reusable, which will reduce the cost per building making it more efficient.

The main advantage of this method is the reduced amount of manual labor. The construction time will be decreased, and the forms can be reused for many different buildings. The problem of drying is still present but using the window screen allows the drying to occur quicker, because the moisture can evaporate from the inside and outside. The main problem with this method is it cannot be protected from rain as would occur in a controlled environment. During the setting period of the papercrete, it is crucial that rain is not in the forecast. After approximately 24 hours, the papercrete sets and a tarp can be draped over the structure to prevent damage from inclement weather.

The weather factor can be reduced by another approach that was taken to strengthen the structure. The final structure will have a thin layer of concrete (Figure 39) that will add strength to the outer shell of the papercrete. Because concrete does not absorb water like papercrete, the outer layer will protect the papercrete from water penetration.

Fig. 39. Concrete layer on papercrete

The concrete layer should be applied as soon as the initial setting of the papercrete occurs and while the papercrete is still wet. The drying process of the papercrete will be slower but the concrete will strengthen because the moisture will allow the hydration reaction to continue to completion.

Concrete gains its strength from the hydration reaction that occurs. The reaction occurs for several months after the concrete is poured; therefore, it is crucial that the concrete stay moist over the first 30 days to maintain enough water for a complete reaction. If the papercrete is allowed to dry before the concrete is applied, the papercrete will absorb the water from the concrete. The papercrete takes the moisture out of the concrete, preventing the hydration reaction from reaching completion, therefore weakening the concrete. However, if the concrete is applied to the papercrete while the papercrete is still wet, the papercrete will keep the concrete moist for several weeks. This slows the drying of the papercrete, however the strength of the papercrete is not as crucial because most of the stress will be placed on the concrete and the forms. The concrete will also protect the papercrete from rain. The concrete can be waterproofed with a less costly coating than the papercrete requires. Overall this method appears to be less costly than the pre-cast wall panel construction, and just as feasible.

CHAPTER X

COST ANALYSIS

10.1 Introduction

Cost analysis of a model building will define the economic factors of papercrete to determine its feasibility as an alternative to current building materials. The data from the structural analysis will be used to determine the quantities of the building materials required. The concrete, paper, and sand values were current market values from May 2006. The cost of the cement was \$90 per ton (U.S. Geological Survey January, 2006), the recycled newspaper was \$75 per ton (Central Texas Recycling Association 2006), the cost of sand was \$22/yd^3 (All American Stone and Turf 2006), and the cost of the pea gravel was \$30/yd (All American Stone and Turf 2006). The cost of cement is an extrapolation of historical cement prices. The recycled newspaper and sand were quotes from local wholesalers. The product of the structure data and current cost factors provide the basis for economic evaluation. The analysis will also determine the cost of the layered papercrete-concrete quonset structure compared to the cost of the same structure constructed completely from concrete. Additionally, the layered quonset structure will be compared to a building constructed from steel with similar dimensions.

10.2 Papercrete-Concrete Quonset Structure

This cost comparison analysis section defines different structure sizes to create a cost analysis that illustrates the most economical building size. The structural analysis process used to defined the building factors for a 20-foot arch was also utilitized on 50-, 100-, 200-, and 400-foot arch structures. This initial analysis (Table 10) only includes the costs of the papercrete, concrete, and wire needed for the structure. The cost does not include labor and equipment nor materials needed during the construction that can be removed and reused. These additional cost factors could materially affect this cost analysis.

Table 10. Diameter Cost Analysis

Diameter (ft)	$/ft^3	$/ft^2
400	0.19	27.75
200	0.15	5.47
100	0.27	2.53
50	0.31	0.73
20	0.38	0.14

Table 10 shows that there is not an optimal cost per square foot; the cost is always lower at a smaller diameter. However, there is an optimum cost per cubic foot. The lowest cost per cubic foot would be a structure with a diameter of approximately 200 feet (Figure 40). The cost would be approximately $0.14/ft^3.

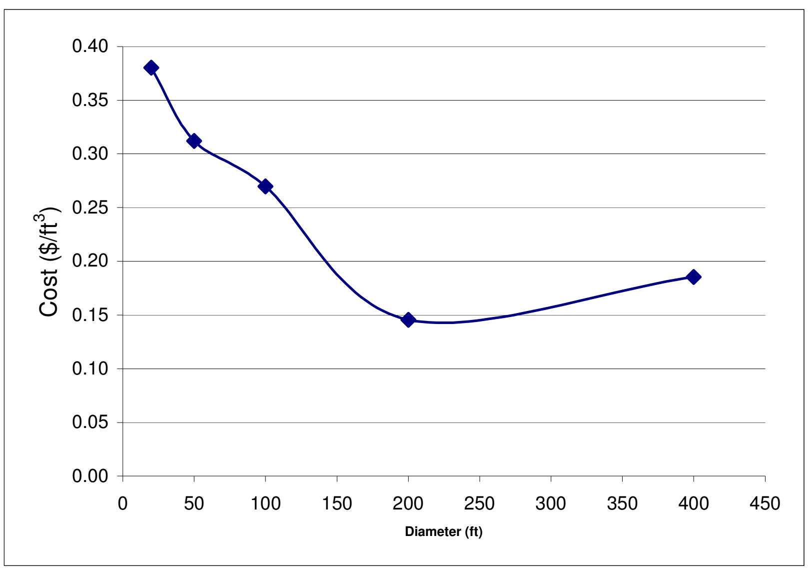

Fig. 40. Material cost of papercrete-concrete quonset structure as a function of diameter

This initial cost estimate includes only material costs determined by the finite element analysis. The 200-foot structure would require the papercrete to be approximately 3.3 feet thick at the base, and the layer of concrete covering the papercrete inside and out would be 2 feet thick. A fillet at the base of the structure approximately 3 feet tall by 3 feet wide at the base would be required. A major concern is the length of time needed for the papercrete to dry. Mass transfer of water in papercrete is reduced with increasing wall thickness. The reduction in mass transfer means the drying time will increase. If the papercrete is not completely dry, the strength will be reduced and the structure will be compromised. The concrete layer that will cover the papercrete will also increase the drying time; therefore, the total drying time of a structure with a 200-foot diameter may take many months. Likely, active heating will be required to reduce the drying time.

There are no catalog-ready steel Quonset buildings available with a 200-ft diameter. To determine the cost of such a structure, it must be custom engineered, which is beyond the scope of this project. However, smaller buildings are available.

10.3 Metal Quonset Structure

This cost analysis compares a papercrete-concrete Quonset structure with the cost of a metal building. The metal structure will have the same general shape as the proposed papercrete-concrete structure, but a cost estimate was obtained from Miracle Span Building Systems, which manufactures commercial buildings. The company makes and then ships modular pieces to the location where the building will be erected.

A range of price estimates was obtained for structures that ranged from 20 to 70 feet wide. Structures this size are pre-engineered and are ready to be shipped for assembly. The cost estimate is for the metal and assembly materials needed. The cost of shipping and assembly are not included in the price; therefore, the cost will be directly comparable to the cost of material for a papercrete-concrete structure. Figure 41 shows the cost per cubic foot of storage space.

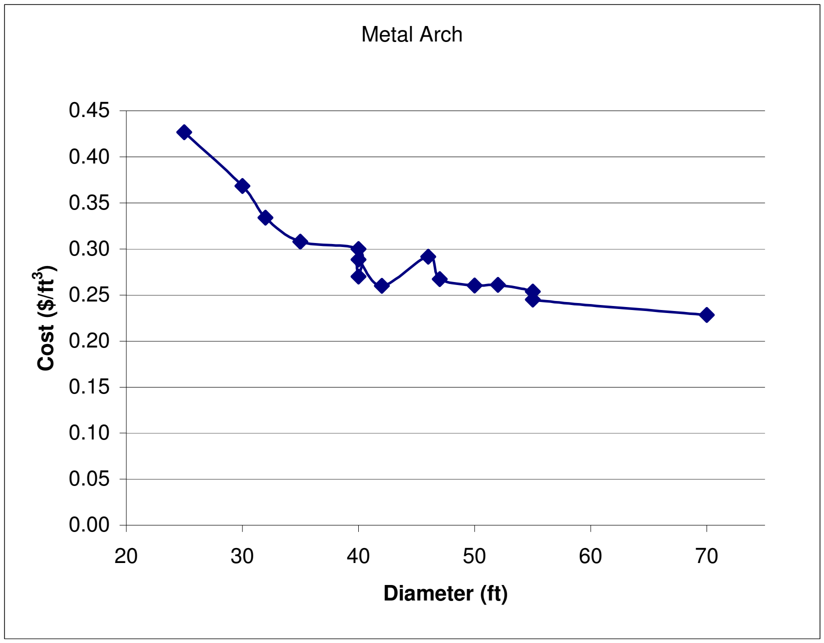

Fig. 41. Metal arch cost analysis (Miracle Steel Structures 2001)

10.4 Steel-Papercrete Comparison

The main objective of this research was to compare the cost of a papercrete structure to other common building materials. It was already determined that a papercrete-concrete structure will be more economical than a completely concrete structure; therefore, papercrete can replace concrete in low-stress interior areas, while maintaining a structurally sound building.

The cost analysis in this section will evaluate the cost of the papercrete-concrete and metal structures. The most effective way to compare the different building materials is to compare similar size structures. Figure 42 illustrates the cost per cubic foot for papercrete-concrete and metal structures. The papercrete-concrete structure is more economical at small sizes; however, after the diameter of the building reaches 31 feet, steel becomes more economical. Larger structures can encase larger quantities of material and therefore are more economical. Therefore, it appears that steel structures will be more cost effective for large-scale pretreatment and fermentation programs. However, the papercrete-concrete structure does provide significantly more insulation than a metal building. Depending on the climate this may or may not be an important consideration.

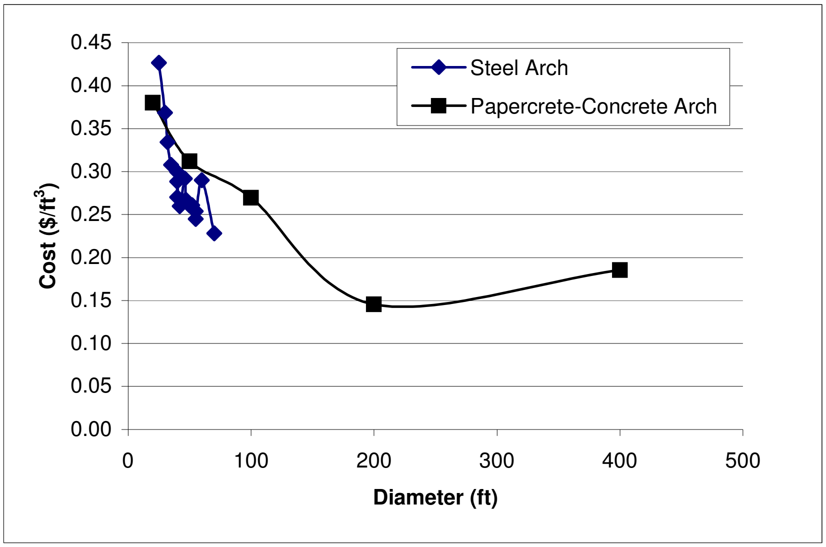

Fig. 42. Comparison of steel to papercrete-concrete structure

A pilot-scale pretreatment and fermentation pile will need an encasement structure that is approximately 20 feet in diameter. At this small scale, the analysis shows that it would be more economical to construct the quonset building from papercrete-concrete. However, to provide an economical building of large scale, the cost of the papercrete-concrete structure is greater than a metal building. The main objective of this project was to conclude whether a papercrete quonset building would be more economical than traditional building materials for covering pretreatment and fermentation piles. A large metal building (70-ft diameter) would be more economical and would cost approximately $\$0.23/ft^3$ of storage space. This would be about $\$0.06/ft^3$ less than a building constructed from papercrete and concrete. The papercrete-concrete building would cost 25% more for building materials.

CHAPTER XI

SUMMARY AND CONCLUSIONS

This study identified and evaluated a wide range of data about papercrete. Papercrete is a very unique building material that can be used for many purposes. The focus of this study was mainly on use for large structures to cover piles for the MixAlco process.

The strength of papercrete was measured to determine the amount of material needed for the pile encasements. A structure made completely of papercrete would be difficult to construct due to its low strength; therefore, a composite structure was studied. A papercrete-concrete structure was evaluated to determine strength characteristic and the amount of material needed to construct a building that would withstand a 100-mph wind. After the finite element analysis was performed, the cost of each size building was calculated, and compared to metal buildings of similar size. The analysis showed that the papercrete structure was more economical for building material for structures up to 31 feet in diameter. However, to benefit from economies of scale and minimize total cost of the pretreatment and fermentation process, a large-scale building would be needed, for which a metal building would be more economical. This does not mean that papercrete could not be used to construct the building; however, it would be more expensive. Papercrete has an advantage of providing insulation, which may have value in certain climates.

The cost analysis determined that the pilot scale papercrete structure, measuring 20 feet in diameter, would be cost effective. Additional structural analysis could be used to optimize material quantities needed for the structure. If the analysis showed similar results, a prototype building should be constructed to get an estimate for the cost of labor needed to construct a Quonset structure using the monolith building method. Such a study could more accurately assess the total cost of the building, and project the total cost of large-scale buildings.

CHAPTER XII

FUTURE WORK

Costs of materials for this study were determined in May 2006. With the escalating cost of metal, the price of traditional building materials could increase faster than the cost of the papercrete. In this case, the papercrete could be come more economical and therefore future studies could find papercrete to be a more economical approach for larger-scale buildings.

This study was an estimate of the cost of constructing a building from papercrete, and little optimization was used to minimize to amount of material used. A further study should be launched to optimize the use of papercrete in building structures. It is suggested that a pilot scale building should be constructed from the papercrete to determine labor costs and material workability. Because the papercrete was found to be economical for small-scale structures, it could be used for emergency housing or small homes.

Another approach to reducing the amount of material in the structure would be inducing a vacuum on the inside. The vacuum could be used to counteract the wind force; this would reduce the required material needed for the structure therefore reducing the cost of the papercrete-concrete structure. A study would be needed to determine if the vacuum could reduce the cost of the structure enough to make the papercrete-concrete structure less expensive than the metal building. The study would need to evaluate different vacuum pressures on the inside to determine how they affect the required amount of material. This could dramatically reduce the cost of the structures, and therefore making the papercrete-concrete structure more economical than other building materials.

A pilot-scale study could also provide insight into the long-term degradation of the papercrete. This study could provide insight into maintaining the material to prevent a catastrophic failure. Long-term maintenance of the material could be minor; however, small damage to the surface could allow water to penetrate the concrete and weaken the papercrete structure to the point of failure.

Extracting water between the mixing and forming stages could increase the strength of papercrete. This would increase the density of the material, which will increase its strength. The process would need to be explored to determine the exact amount needed to be extracted to maintain a consistent mixture. Catastrophic failure could occur if less water is extracted than is required. A study would need to be performed to determine if the water could be extracted appropriately to maintain structurally sound quonset building. If inconsistencies occurred throughout the structure, “weak spots” would be possible points of failure. This may involve building a prototype structure and testing its strength to determine its maximum load bearing capability.

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APPENDIX A

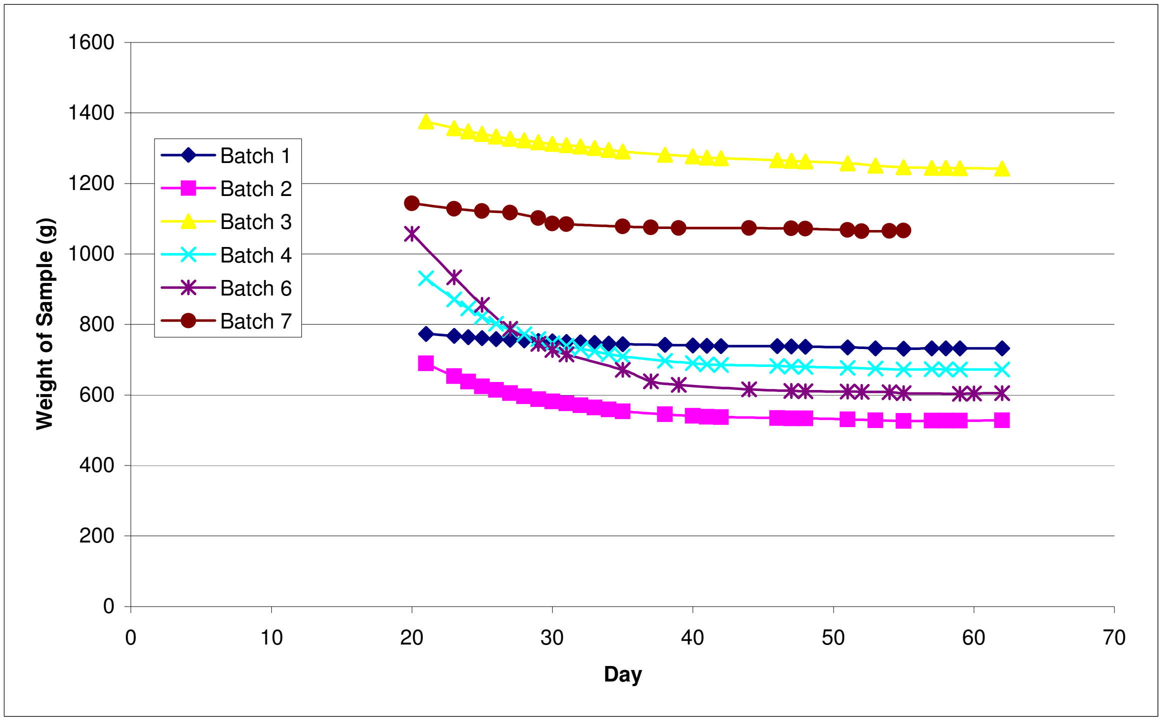

Fig. A1. Papercrete batch drying times

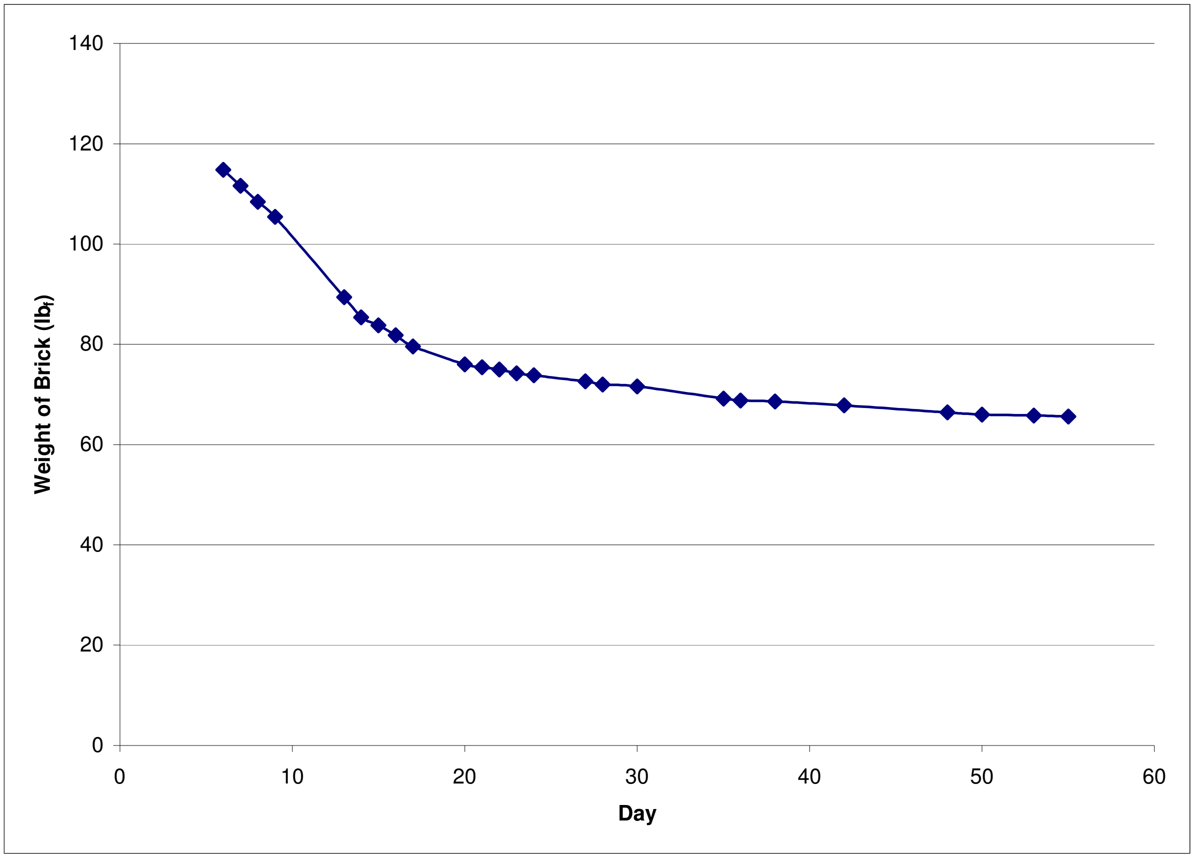

Fig. A2. Papercrete drying time for prototype wall panel

APPENDIX B

Table B1. Papercrete batch compositions

	% Paper	% Cement	% Sand	Water Content (mL water/g of paper)
Batch 1-1	40.0	60.0	0.0	11.5
Batch 2-1	60.0	40.0	0.0	11.5
Batch 3-1	20.0	60.0	20.0	11.5
Batch 4-1	40.0	40.0	20.0	11.5
Batch 6-1	40.0	20.0	40.0	11.5
Batch 7-1	20.0	40.0	40.0	11.5
Batch 3-2	20.0	60.0	20.0	13.8

Table B2. Summary of papercrete batch properties

	Compressive Strength (psi)	Tensile Strength (psi)	Modulus of Rupture (psi)	Shrinkage (%)	Density (lb/ft^3)	Cost ($\$/ft^3$)
Batch 1-1	37.2	16.5		11.0	19.7	0.62
Batch 2-1	37.0	9.1		11.5	16.4	0.65
Batch 3-1	143.6	28.3		9.8	32.8	0.95
Batch 4-1	29.8	7.5		12.5	18.8	0.78
Batch 6-1	28.3	10.4		14.5	18.2	0.46
Batch 7-1	56.6	14.6		11.1	29.5	0.75
Batch 3-2	74.8	20.9	62.1	0.0	0.0	0.85

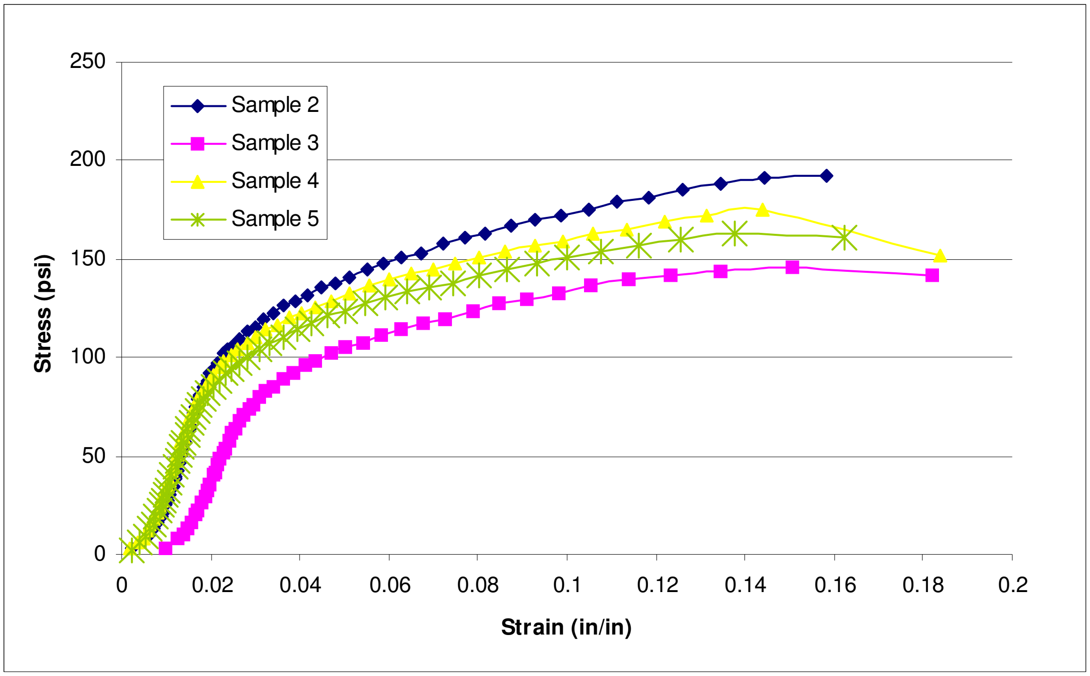

Fig. B1. Papercrete Batch 1-1 compressive stress-strain

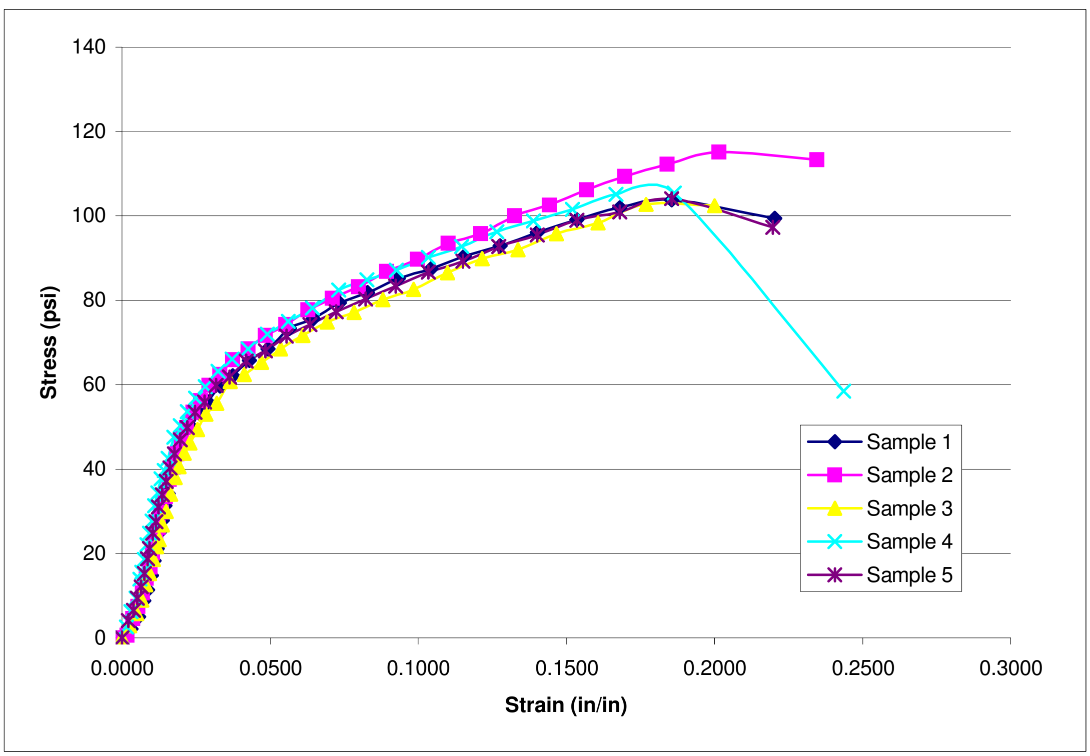

Fig. B2. Papercrete Batch 2-1 compressive stress-strain

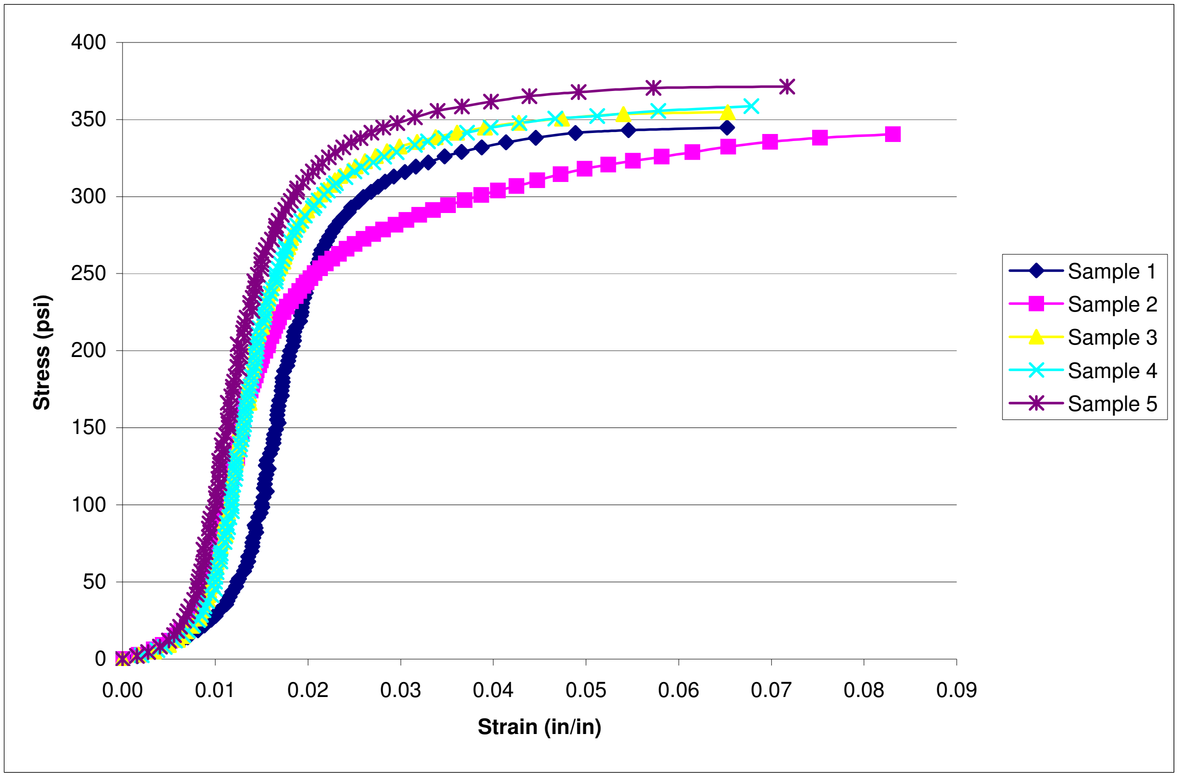

Fig. B3. Papercrete Batch 3-1 compressive stress-strain

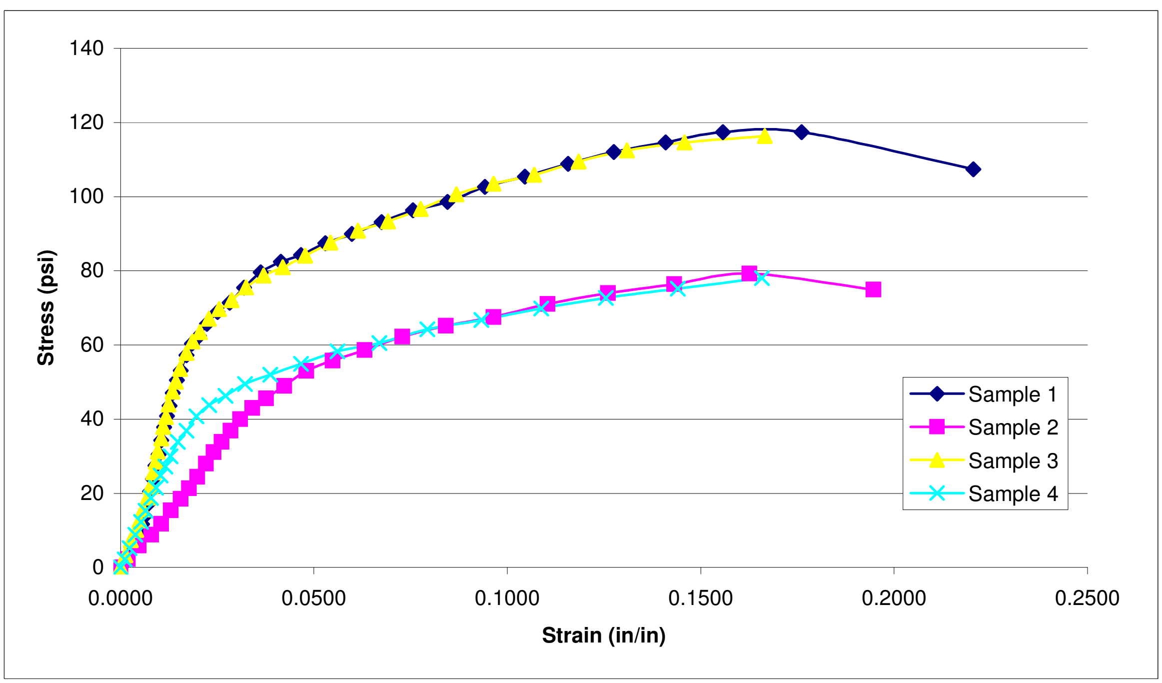

Fig. B4. Papercrete Batch 4-1 compressive stress-strain

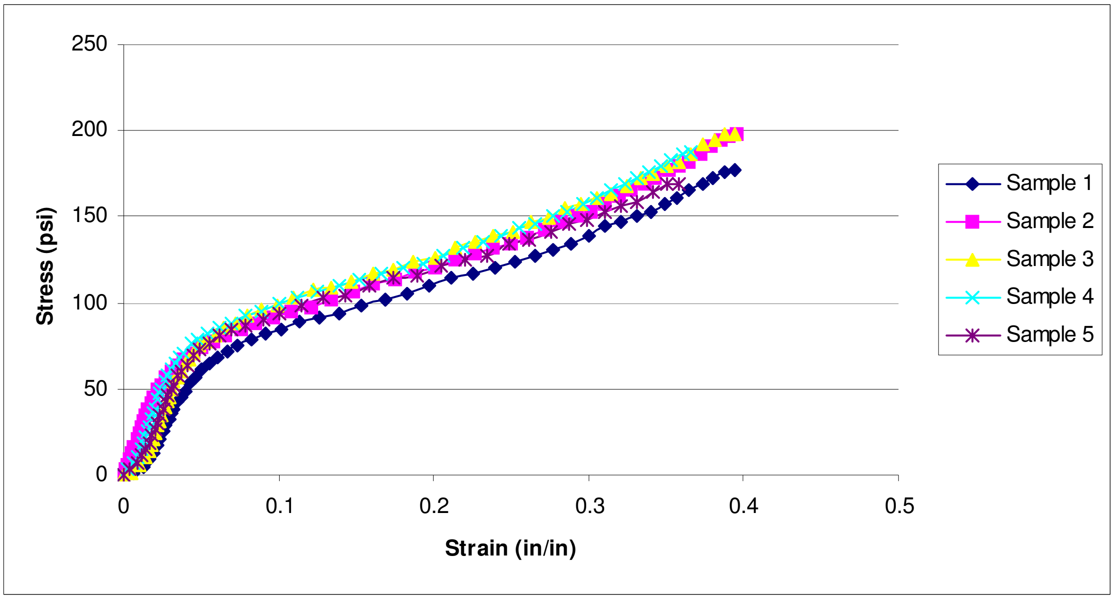

Fig. B5. Papercrete Batch 5-1 compressive test stress-strain

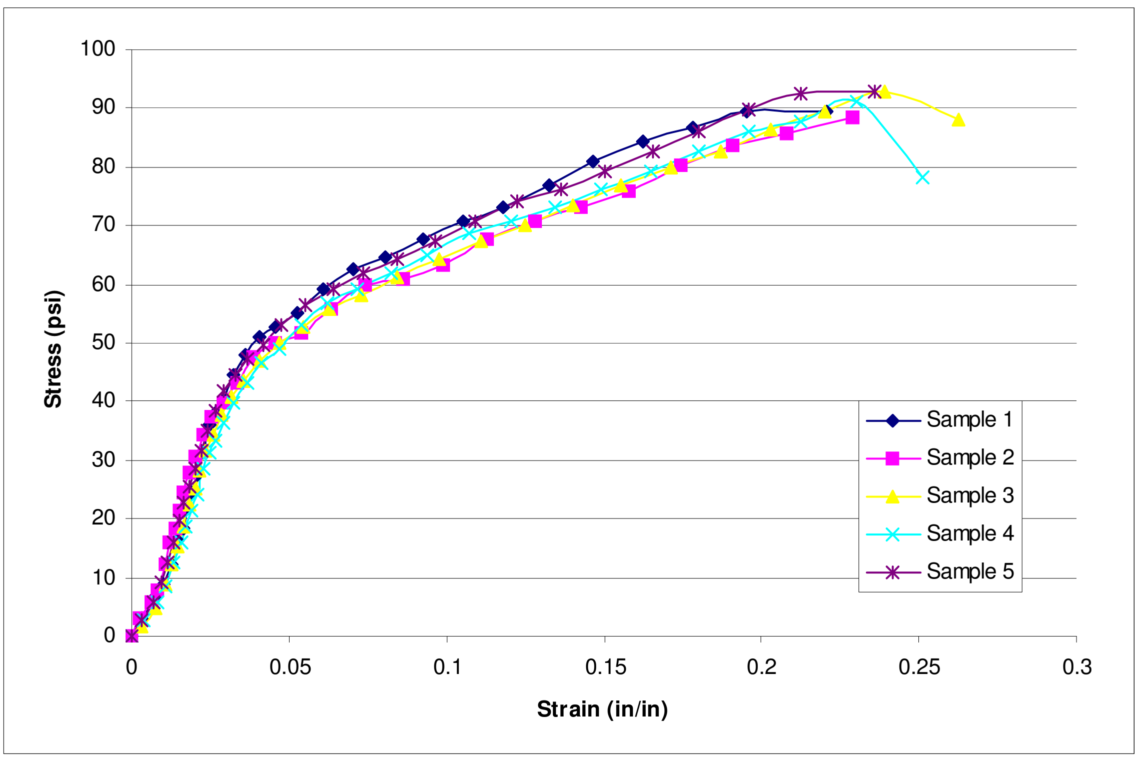

Fig. B6. Papercrete Batch 6-1 compressive test stress-strain

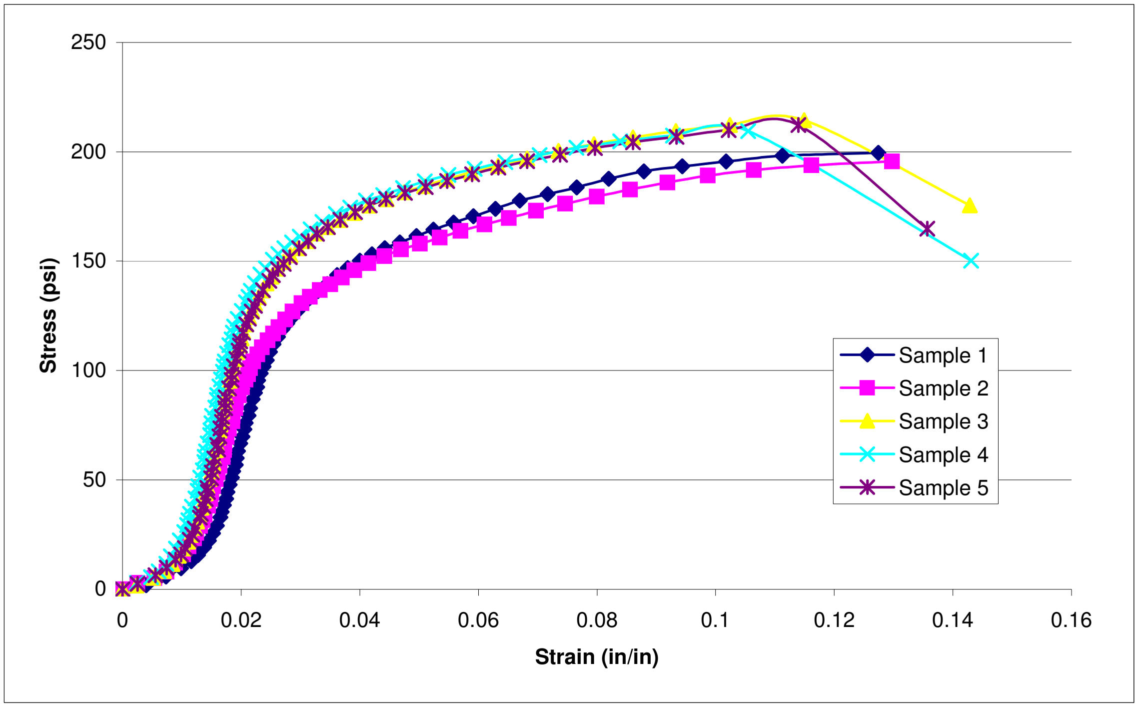

Fig. B7. Papercrete Batch 7-1 compressive text stress-strain

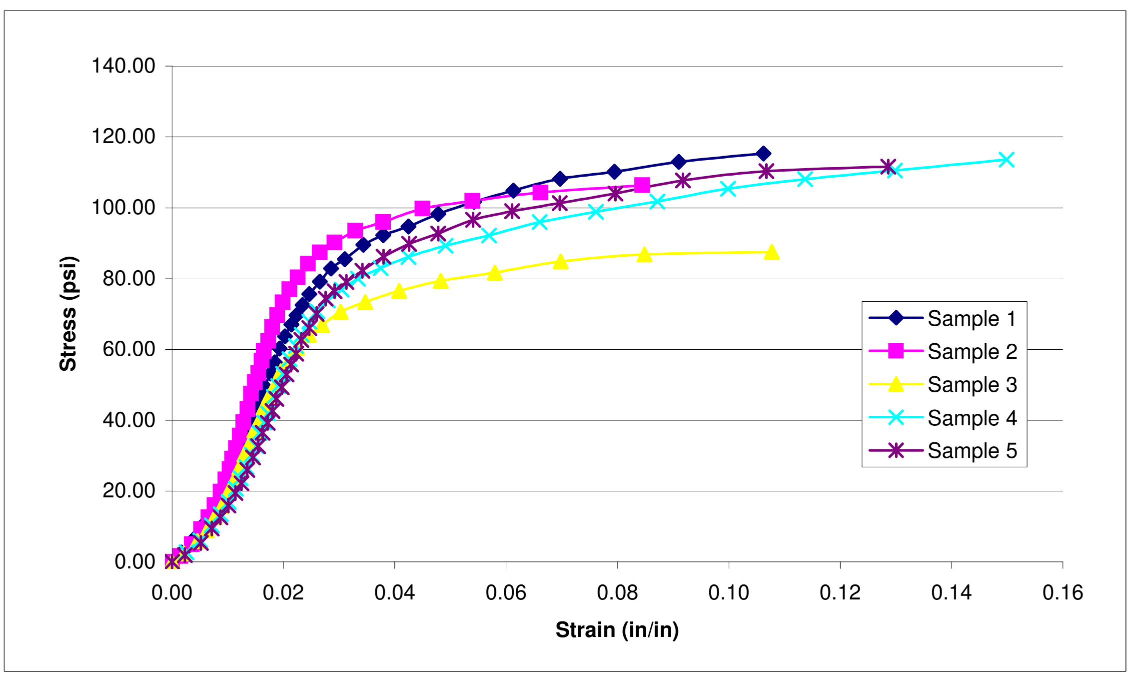

Fig. B8. Papercrete Batch 3-2 compressive text stress-strain

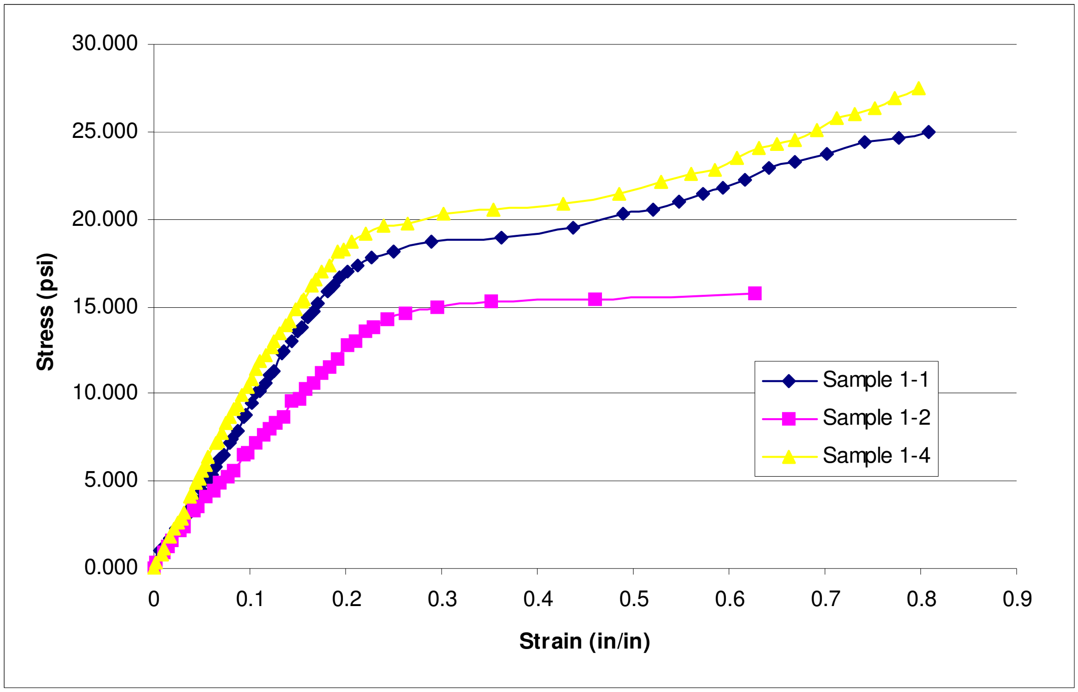

Fig. B9. Papercrete Batch 1-1 tensile test stress-strain

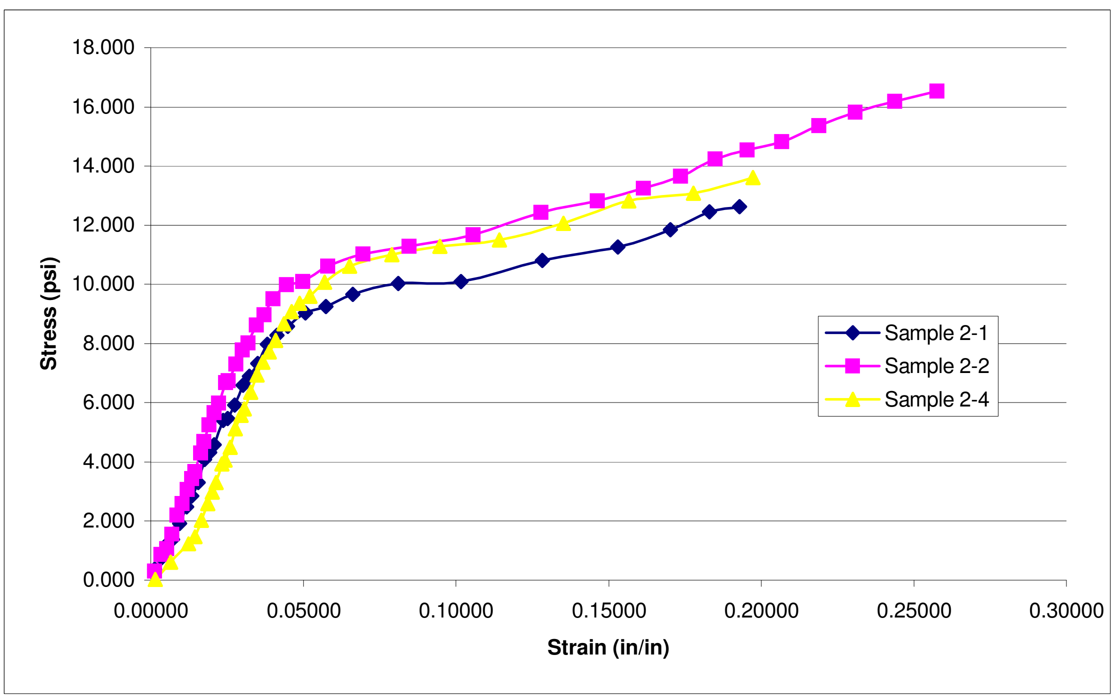

Fig. B10. Papercrete Batch 2-1 tensile test stress-strain

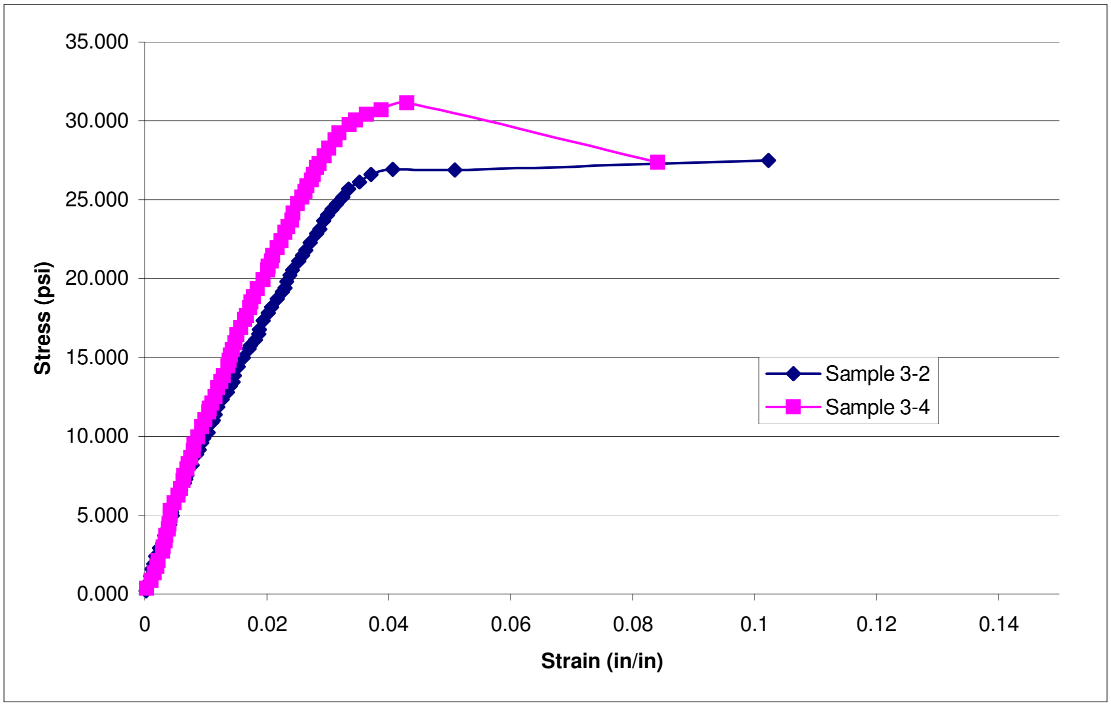

Fig. B11. Papercrete Batch 3-1 tensile test stress-strain

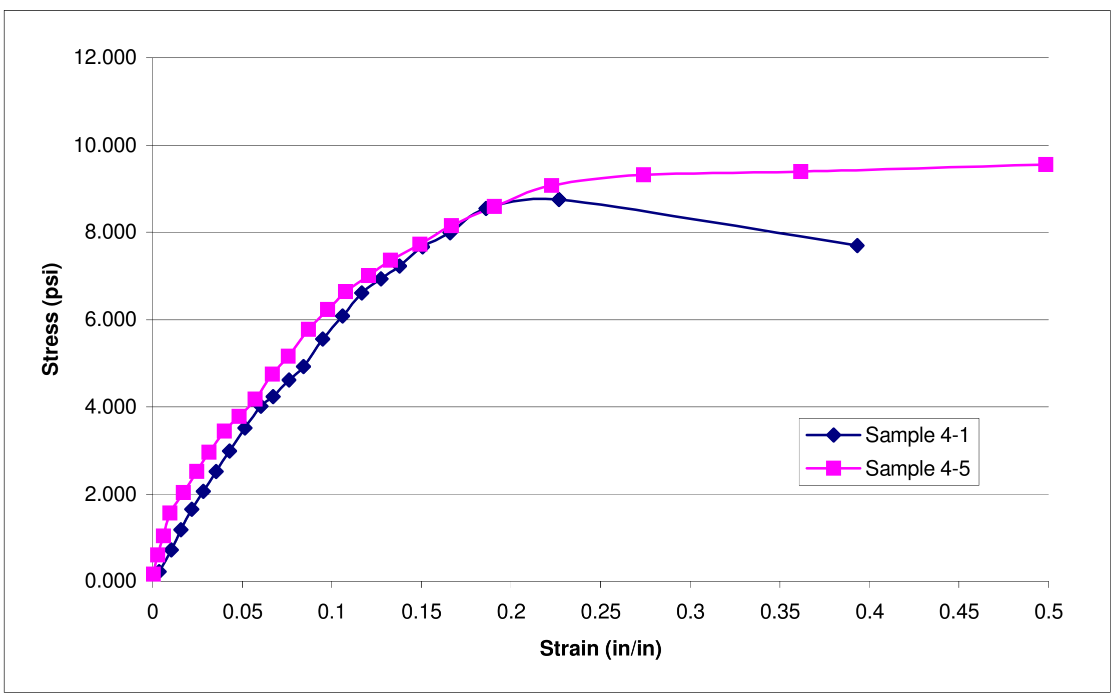

Fig. B12. Papercrete Batch 4-1 tensile test stress-strain

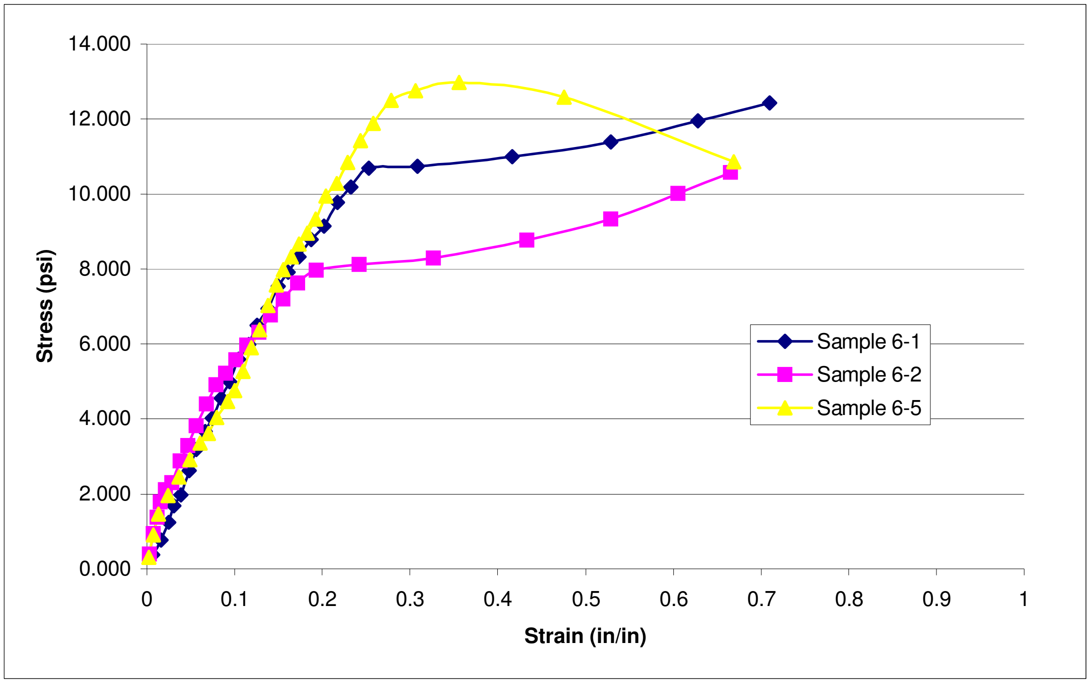

Fig. B13. Papercrete Batch 6-1 tensile test stress-strain

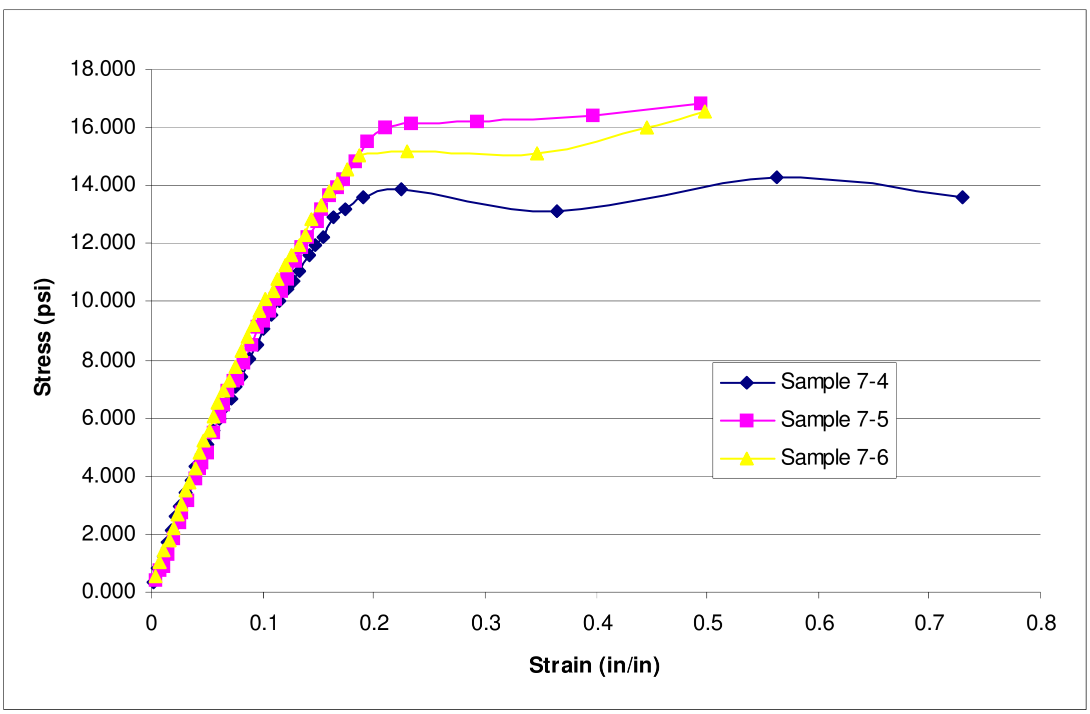

Fig. B14. Papercrete Batch 7-1 tensile test stress-strain

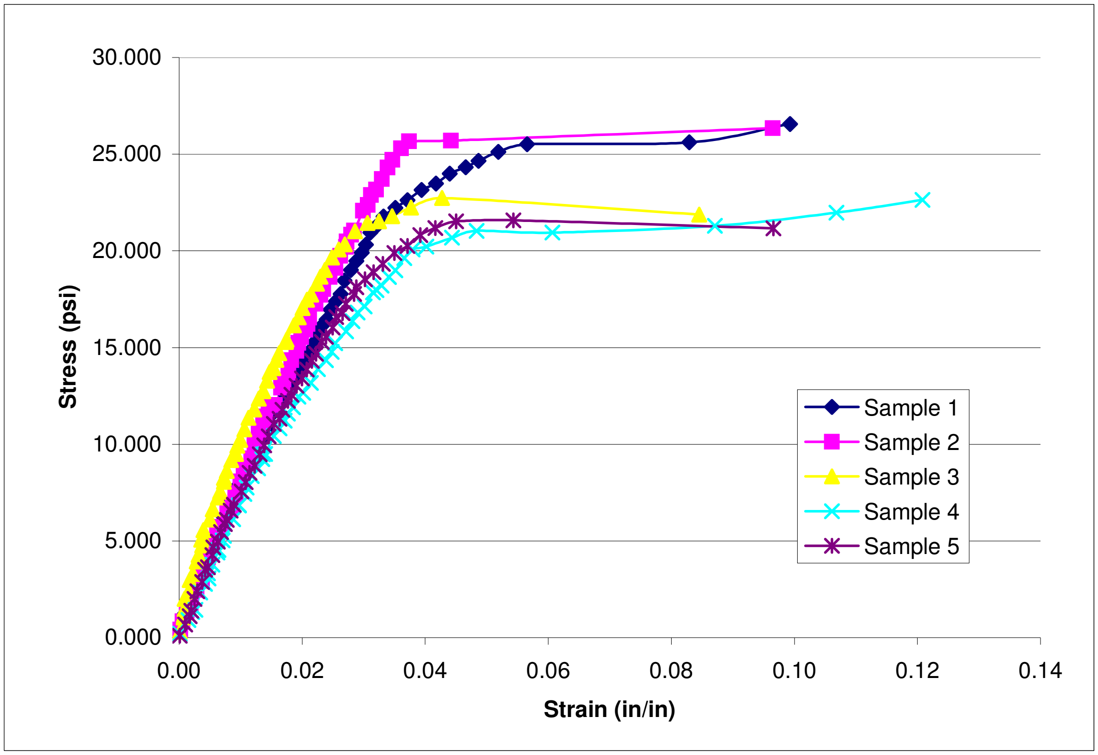

Fig. B15. Papercrete Batch 3-2 tensile test stress-strain

APPENDIX C

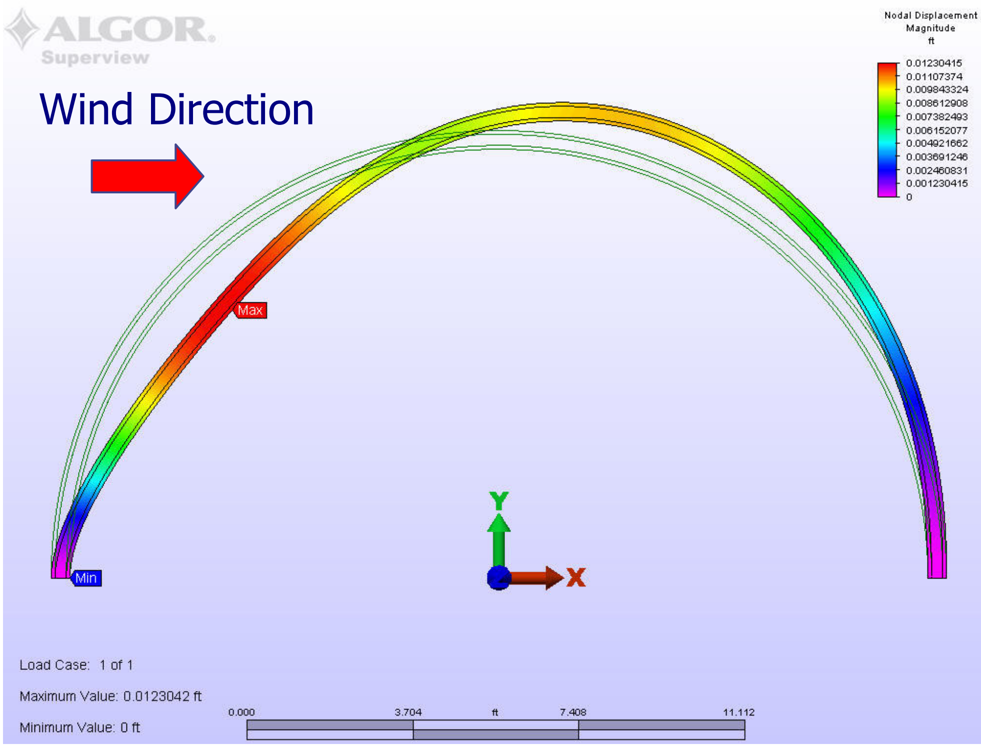

Fig. C1. Maximum displacement (20-ft diameter)

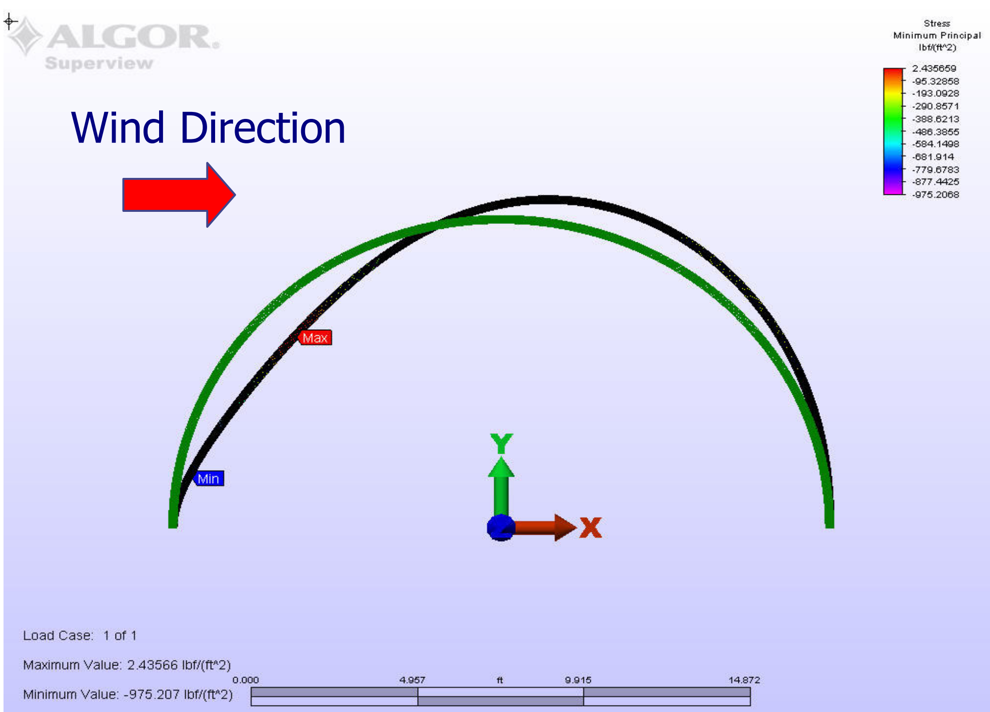

Fig. C2. Maximum compressive stress (20-ft diameter)

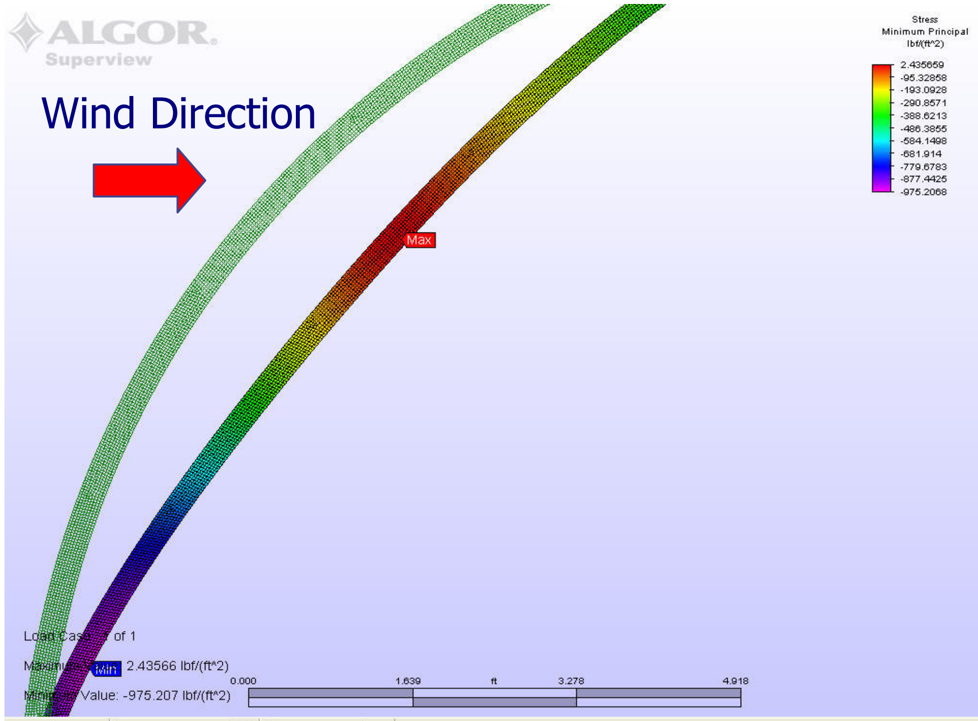

Fig. C3. Maximum compressive stress (20-ft diameter)

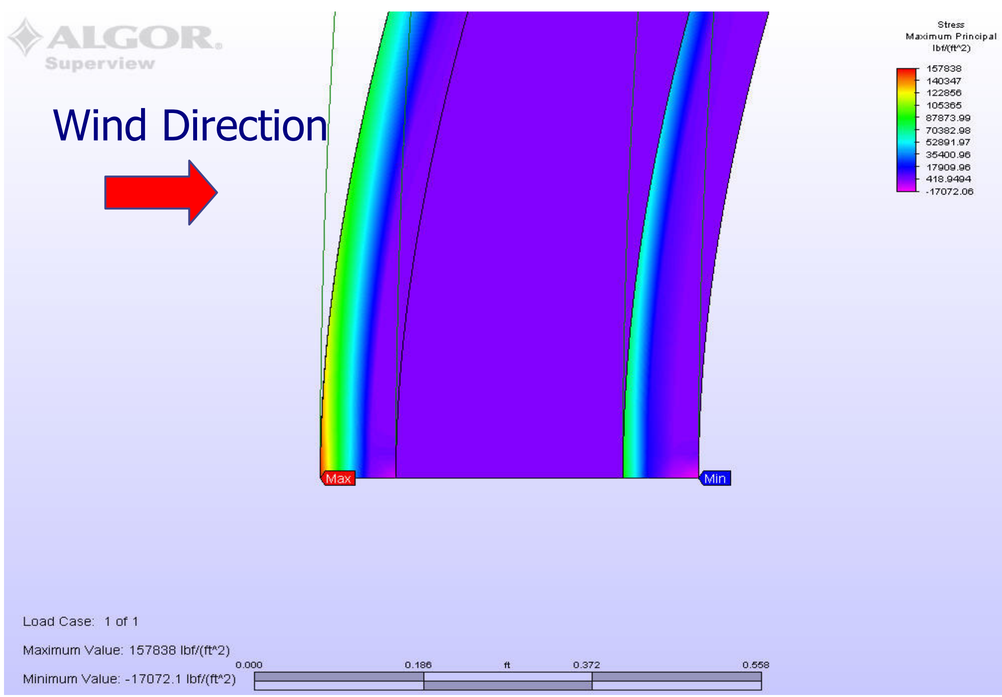

Fig. C4. Maximum tensile stress (20-ft diameter)

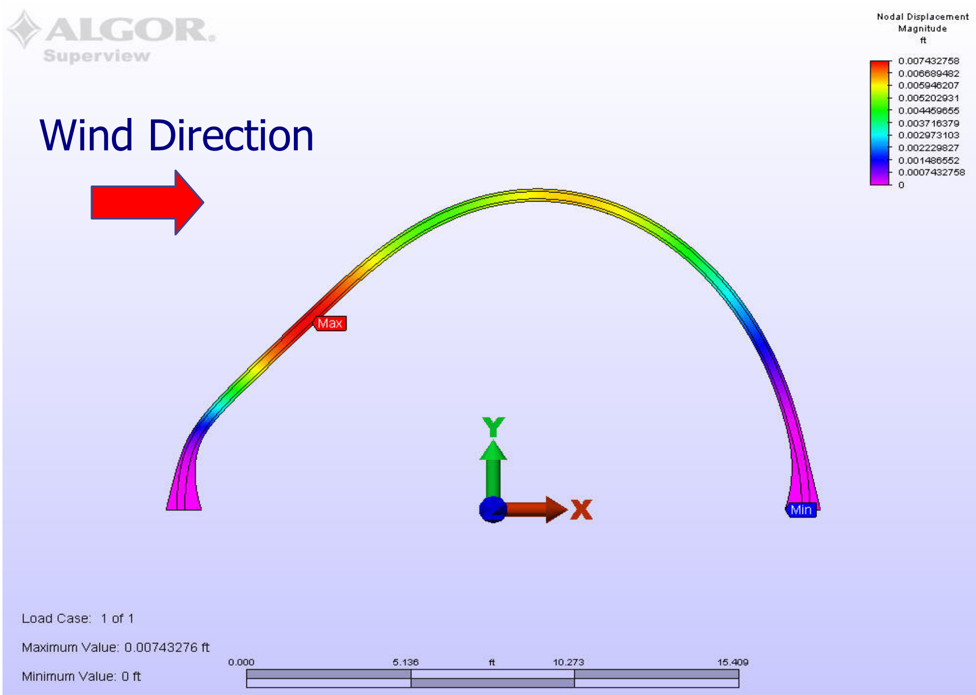

Fig. C5. Maximum displacement (modified 20-ft diameter)

Fig. C6. Maximum compressive stress (modified 20-ft diameter)

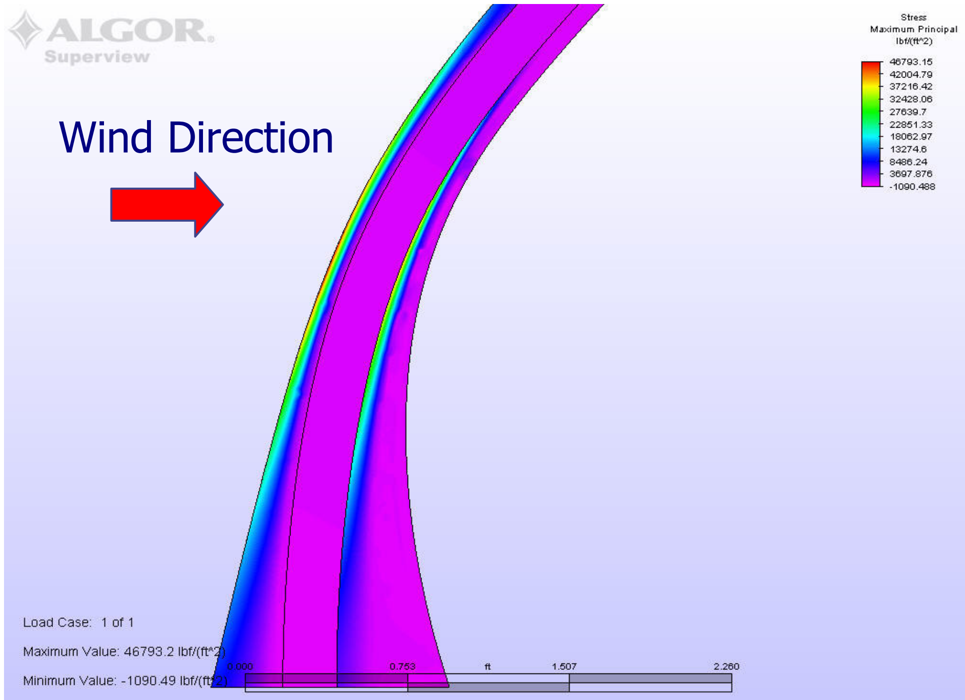

Fig. C7. Maximum tensile stress (modified 20-ft diameter)

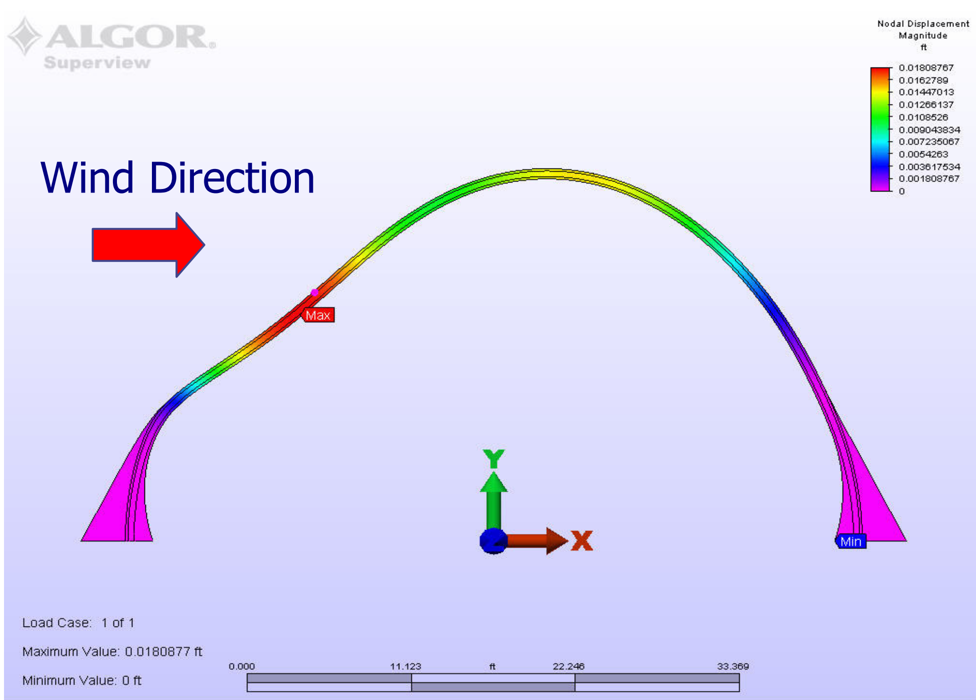

Fig. C8. Maximum displacement (50-ft diameter)

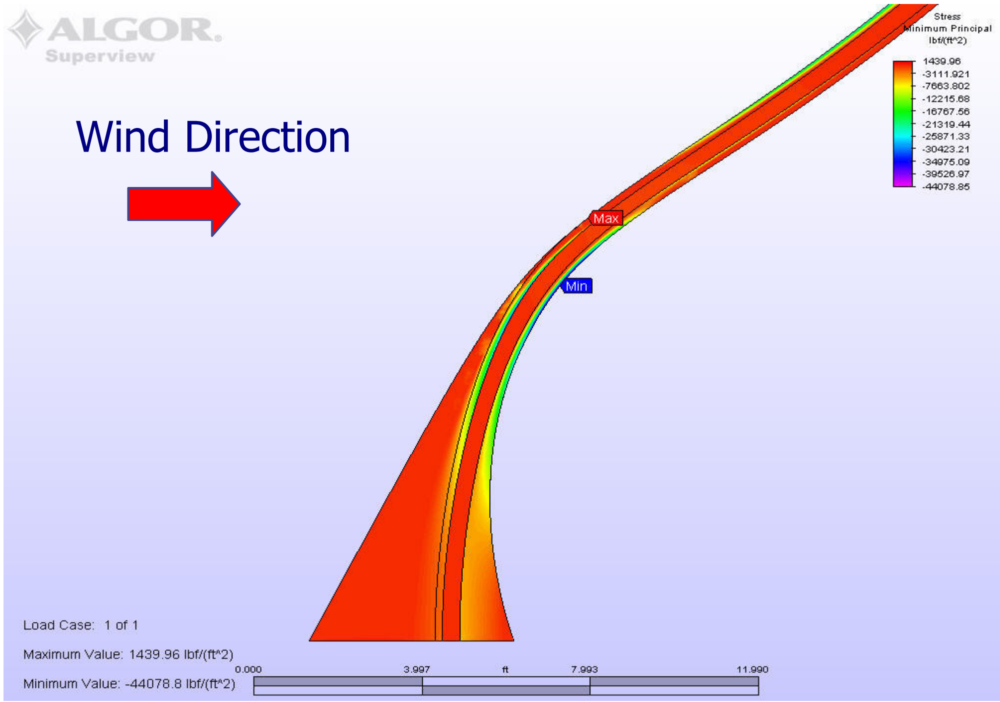

Fig. C9. Maximum compressive stress (50-ft diameter)

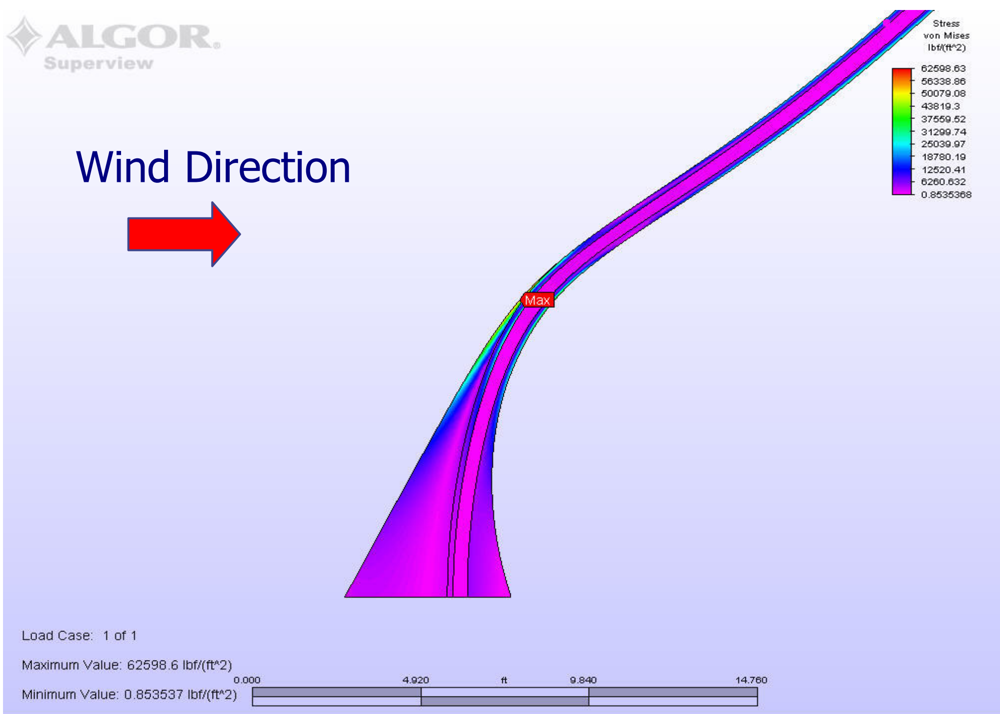

Fig. C10. Maximum tensile stress (50-ft diameter)

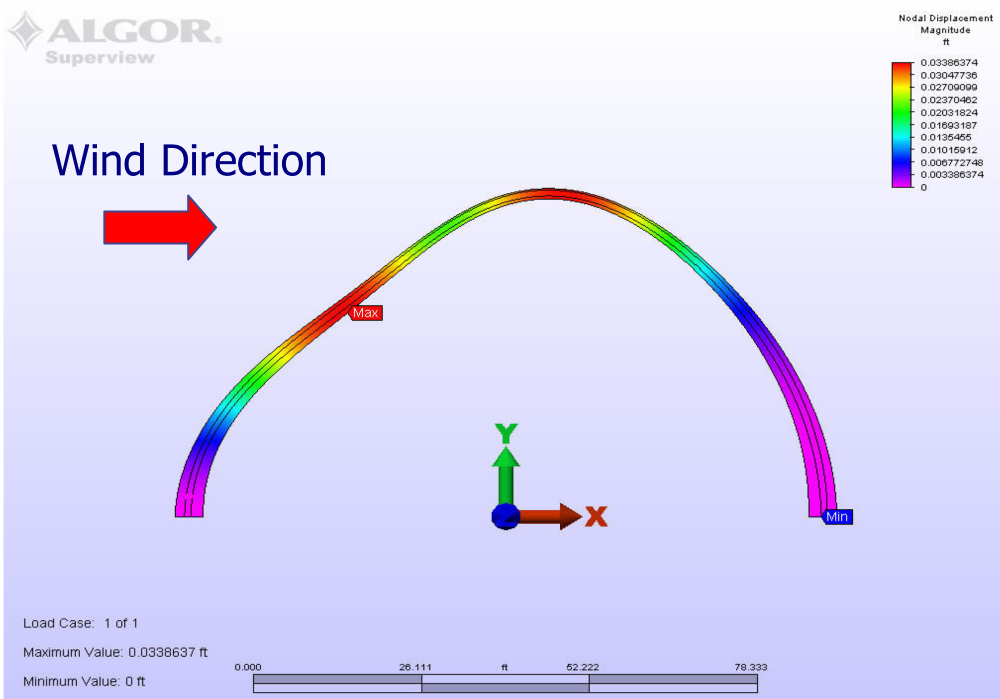

Fig. C11. Maximum displacement (100-ft diameter)

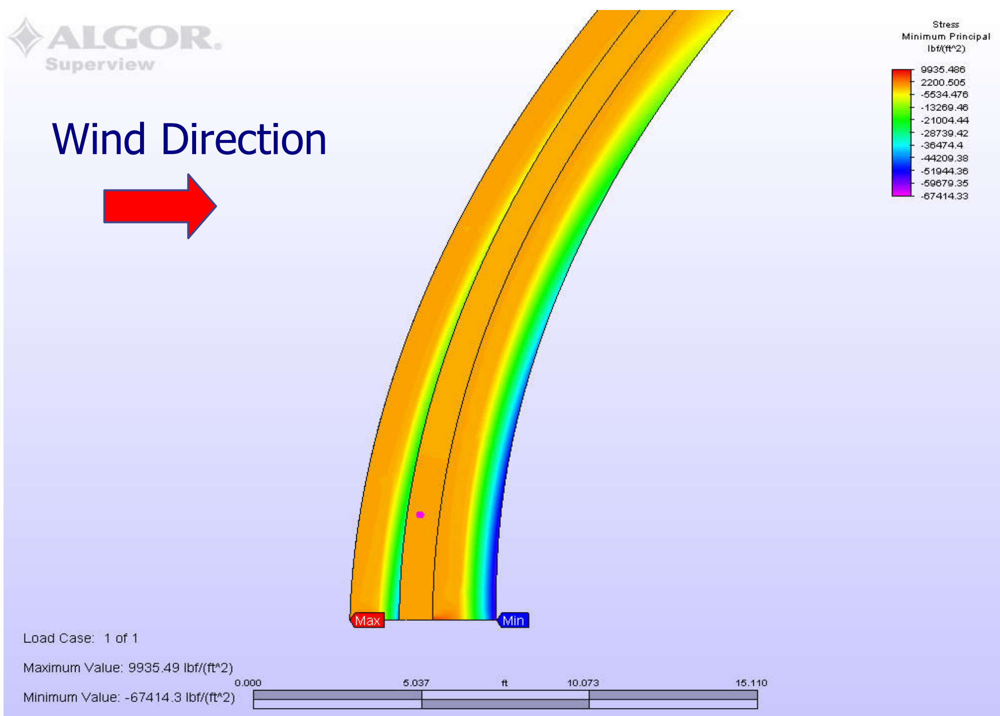

Fig. C12. Maximum compressive stress (100-ft diameter)

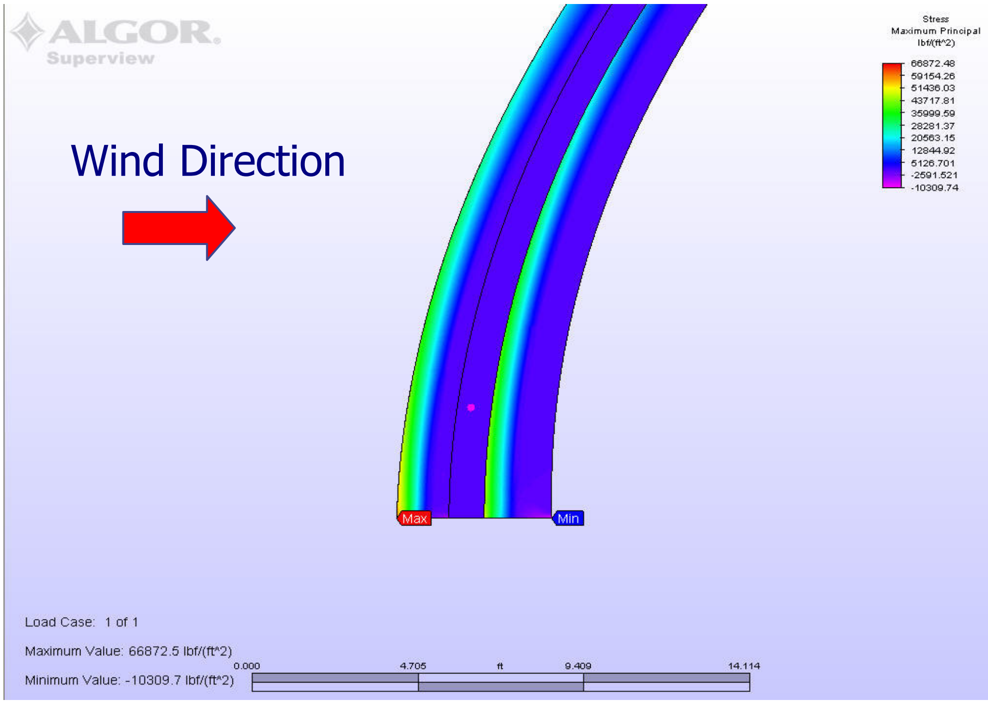

Fig. C13. Maximum tensile stress (100-ft diameter)

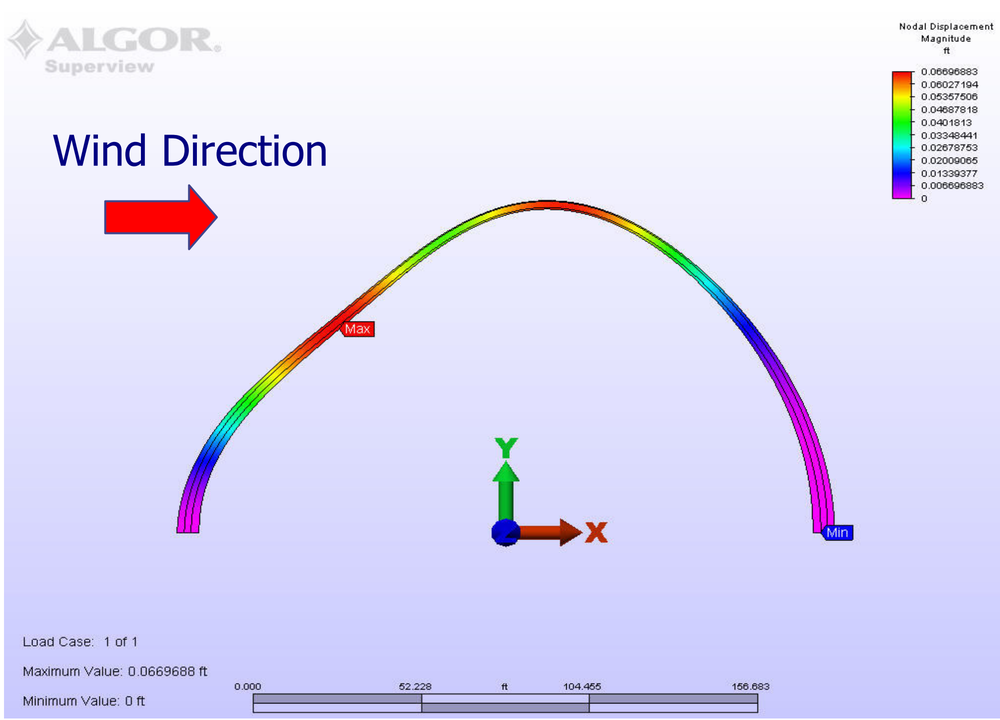

Fig. C14. Maximum displacement (200-ft diameter)

Fig. C15. Maximum compressive stress (200-ft diameter)

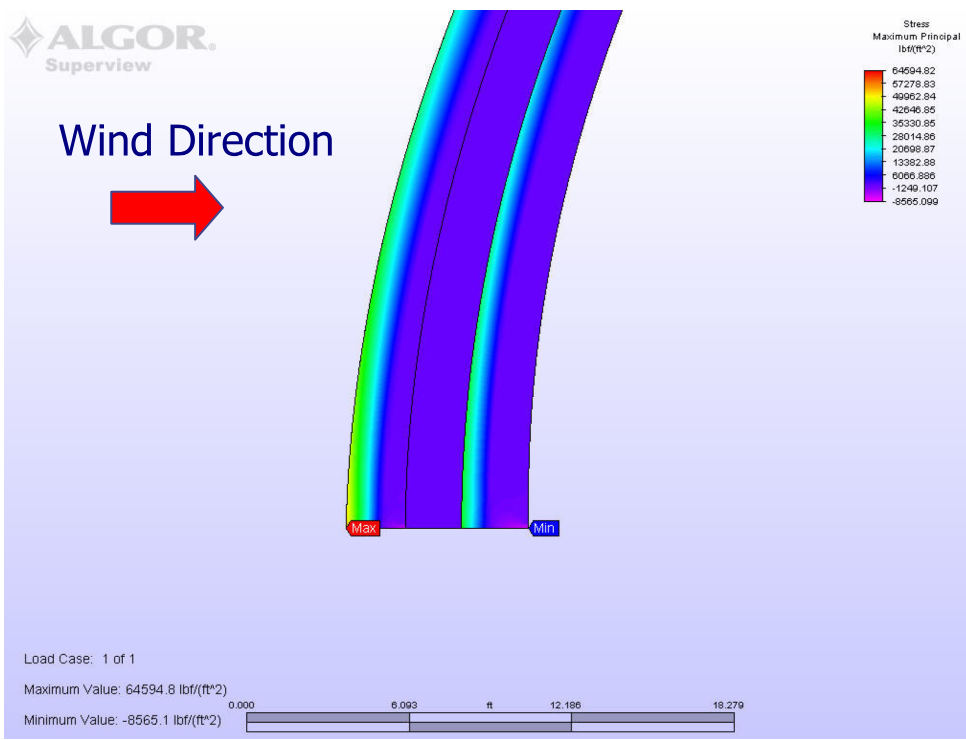

Fig. C16. Maximum tensile stress (200-ft diameter)

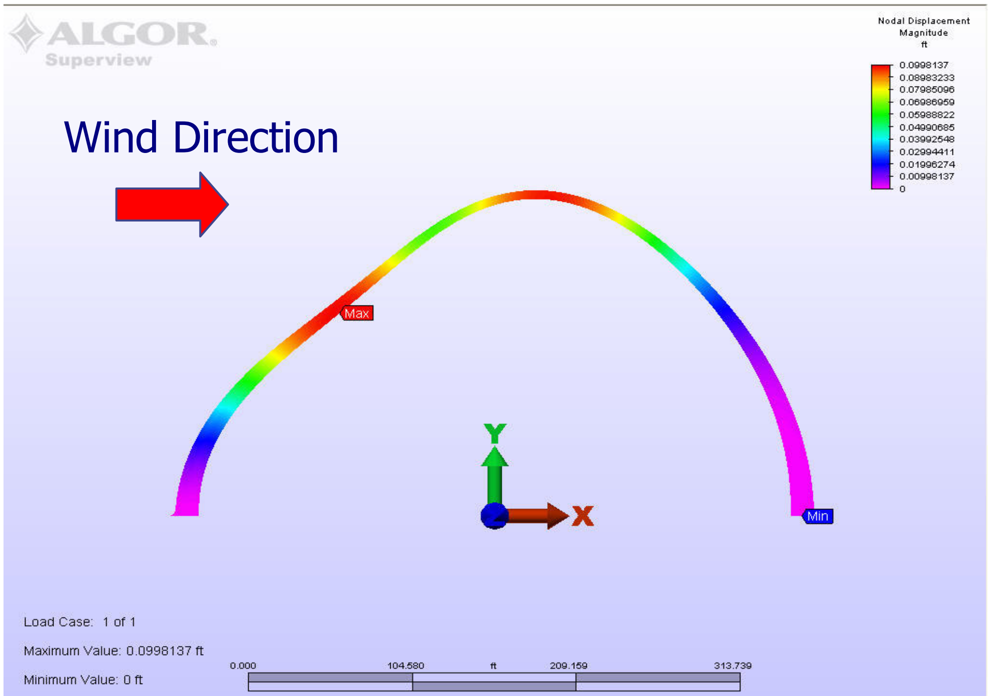

Fig. C17. Maximum displacement (400-ft diameter)

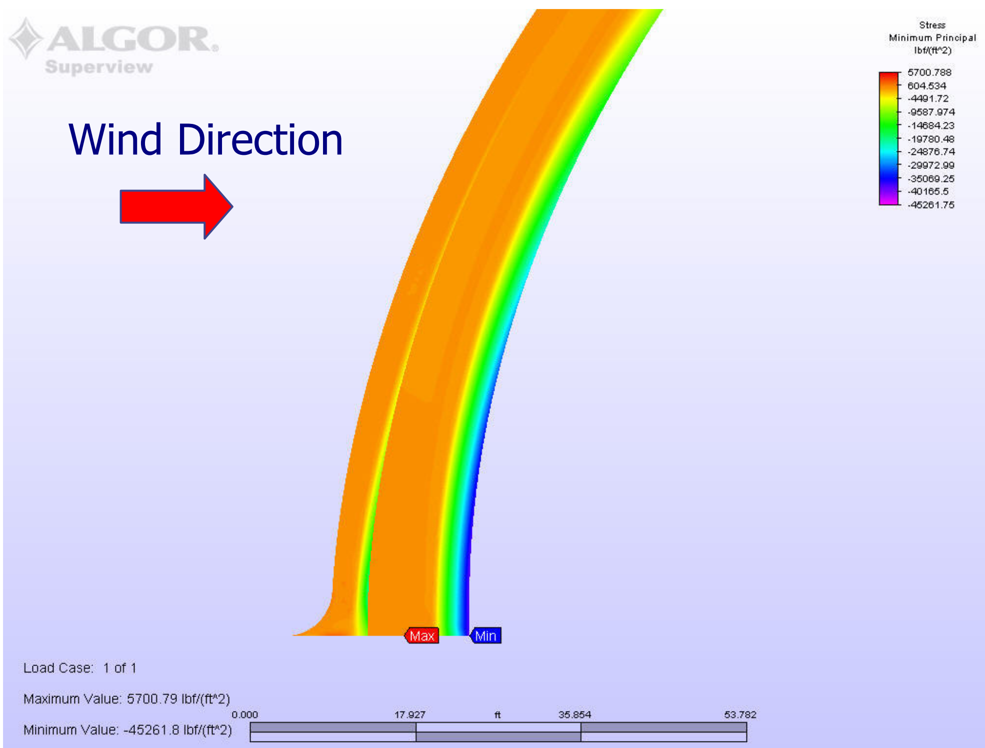

Fig. C18. Maximum compressive stress (400-ft diameter)

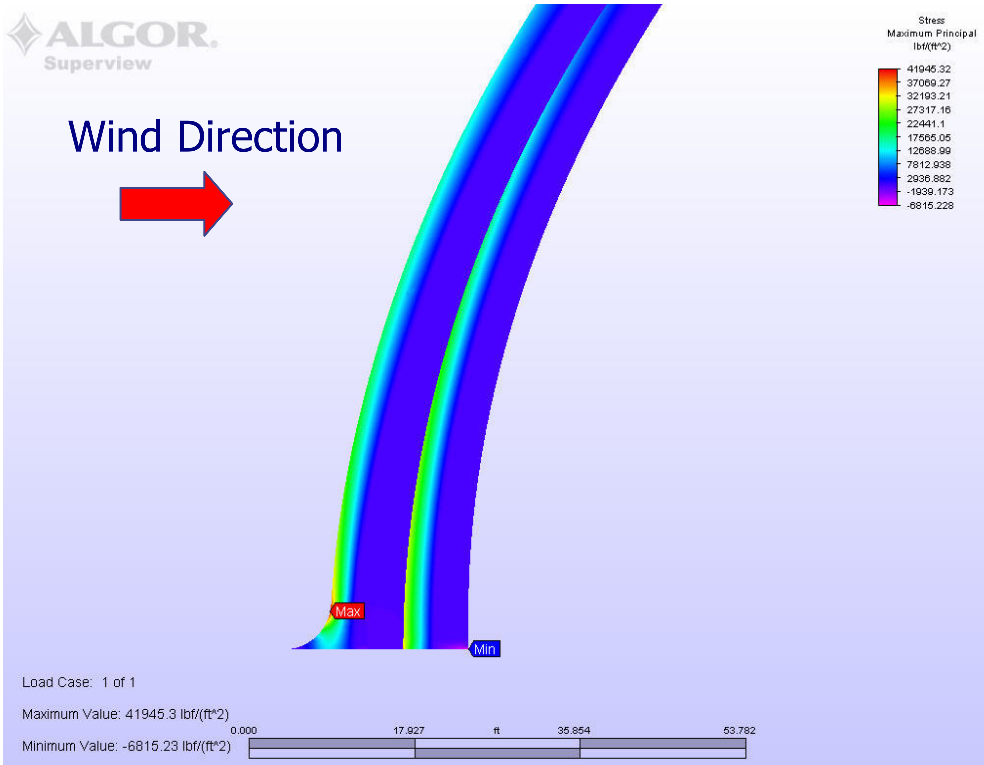

Fig. C19. Maximum tensile stress (400-ft diameter)

Table 11. Papercrete Thickness Requirements

	Base of Arch (ft)	Top of Arch (ft)
20 ft diameter	0.25	0.25
50 ft diameter	0.5	0.5
100 ft diameter	1	1
200 ft diameter	2.1	2
400 ft diameter	4	4

Table C2. Concrete thickness requirements

	Base of Arch		Top of Arch	
	Inside Layer (ft)	Outside Layer (ft)	Inside Layer (ft)	Outside Layer (ft)
20 ft diameter	0.08	0.08	0.08	0.08
50 ft diameter	1.17	1.13	0.15	0.15
100 ft diameter	1.92	1.49	0.52	0.3
200 ft diameter	2.52	2.23	0.5	0.3
400 ft diameter	5	5	1.38	1

Table C3. Concrete fillet requirements

	Inside		Outside	
	Height (ft)	Width (ft)	Height (ft)	Width (ft)
20 ft diameter	1.00	0.25	1.00	0.25
50 ft diameter	-	-	-	-
100 ft diameter	4	4	4	4
200 ft diameter	3	3	3	3
400 ft diameter	5.5	5.5	5.5	5.5

Table C4. Steel building sizes and pricing (Miracle Steel Structures 2001)

Height	Width	Length	Price		Price/ft^3
24	70	100	30120		0.23
20	60	100	27313.6		0.29
18.8	55	100	19899.2		0.25
17.6	55	100	19299.2		0.25
18	52	100	19179.2		0.26
17.6	50	100	18000		0.26
18	47	100	17760		0.27
16	46	100	16,859.20		0.29
17	42	100	14579.2		0.26
20	40	100	18120		0.29
18	40	100	15280		0.27
14	40	100	13187.2		0.30
17	35	100	14387.2		0.31
15	32	100	12596.8		0.33
14	30	100	12156		0.37
12	25	100	10056		0.43

VITA

L. Clinton Titzman was born in San Antonio, Texas. He grew up on a ranch in south Texas, near the town of Falls City, which is approximately 60 miles south of San Antonio. He attended Falls City high school where he discovered his interests in chemistry, mathematics, and physics. He graduated from High School in 1998, and then decided to attend Coastal Bend Community College. While attending Coastal Bend he discovered his interest in chemical engineering. He then transferred to Texas A&M University and graduated with a bachelor of science in chemical engineering in May 2003. After working for a short time, he decided to return to graduate school at Texas A&M, where he joined Dr. Holtzapple's research group. He then graduated in December 2006 with a Master of Science in Chemical Engineering.