Lightweight Concrete: Investigations into the Production of Variable Density Cellular Materials

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Submitted to the Department of Architecture
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Abstract

This research focuses on the intersection between material composition and form in the development of a new type of concrete. As concrete is the most widely used building material in the world, innovation in this material has more potential to effect change in our built environment than innovation in any other. With the objective of minimizing raw material consumption and energy use, this work attempts to develop methods for creating a cellular lightweight concrete with variable density that can be cured at room temperature. Most aerated concretes traditionally require high temperature and high pressure curing; the goal of this research is to create a lower embodied energy product through the use of room temperature curing, while at the same time maximizing performance through variation of the density of the material through its section–essentially locating stronger material where it is needed. This more durable and versatile concrete product will be able to compete with traditional lightweight concretes, which provide benefits such as insulation, as well as normal-weight concrete, which is harder and stronger. The research aims to capitalize on the inherent heterogeneity of the material by producing a substance whose internal properties can be varied based on the needs of a specific part of a building. I am interested in replacing the concept of the "assembly" of materials to gain a desired function with a more unitary concept: the manipulation of a *single* material to meet a building's multiple needs. A desired outcome of the work is to reconceive how we put buildings together, not as assemblies of discrete elements but as monolithic yet malleable wholes.

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Chapter 1: Introduction

This introduction serves to outline the goals and scope of the research conducted for the completion of the SMArchS degree within the Building Technology discipline group. The overarching motivation for this work is the creation of a better concrete for use in building construction. Can we imagine a concrete that can do everything we might want it to do? What would it look like? The primary objective of the project is to develop the ability to "tune" the density of the material, opening up the possibility for better strength-to-weight ratios, the inclusion of thermal insulating capacity, lowered embodied energy, reduced material consumption, and enhanced durability and surface quality. Through the exploration and testing of novel ways of producing concrete, this project has resulted in the invention of a new concrete.

1.1

Contextualizing the Work

In many ways, this thesis occupies the space between a number of different disciplines: architecture, engineering, material science, to name a few. The work has evolved and shifted in its focus at varying points throughout the process. Throughout, though, there has always been a tension in the work that has arisen from a certain ambiguity related to where the work should reside. Because I have a background in architecture and had little engineering training when I started the work, much of the process involved a wrestling with the tensions and sometimes opposing pressures between these disciplines. One of the main contributions I hope this thesis provides is a chance to have a high-level discussion of what it means to work in the spaces between disciplines and what kind of value this type of work might have.

In a concrete sense (no pun intended), this research project is about developing better building materials–materials that are more sophisticated, have reduced environmental impact, and can be used to create more efficient and beautiful buildings. This has meant that a wide range of influences and motivations have guided the work. The technical performance of the materials I have developed has always been a fundamental criterion for measuring the value of the work, but just as important, the aesthetic aspects of the material and the implications for design and even art have always been critical considerations that held just as much importance. I have found that trying to straddle these two worlds has been quite challenging. It is easy to get caught up in either world and lose sight of the considerations inherent in the other. My contention is that this interplay between the technical performance of the material–in a sense the material science and engineering side of the work–and the creative and aesthetic side, has produced a much richer body of work.

There are benefits to working in this in-between space, but also limitations. In a very real sense, this broad approach has limited the extent to which I have been able to push the work in either direction. For example, because I became so invested in developing the casting methods that form the backbone of the experimental work, I had less time to spend testing and analyzing the materials. This constraint can also be seen as a plus because it freed me to be able to push the line of inquiry quite far in a short period of time. There were also knowledge constraints that influenced the work, such as not being formally trained in the micromechanics of concrete. But this sort of limitation in a certain sense freed me to conceive of possibilities that I might have dismissed had I had a more focused and deeper knowledge base within the field at the outset.

My hope is that the reader will be able to appreciate the different modes of thinking that accompanied this work. I want the reader to find this work accessible and valuable–be that reader an engineer, a designer, a scientist, or the lay-enthusiast. This necessarily sets up challenges. There are specific sets of language and terms–ontologies–that surround the different disciplines this work bumps up against. A material scientist is going to talk about concrete in a different way than an engineer, and an engineer is going to use different language than a designer. The material scientist sees concrete as a complex composition of many minerals. The engineer sees concrete as a material that has a certain set of properties associated with it that dictate how it will behave under different conditions. An architect might approach the material in much the same way as an engineer, but is also going to be just as concerned with the aesthetic, tactile and sensory aspects of the material. All of these approaches are valid and valuable depending on one's goals. My hope is that readers from any background will find this investigation into creating variable density concrete approachable and relevant.

1.2
A Brief Overview of the Research

The novel forming process that I have developed opens up the possibility for one to produce a new type of cellular cementitious material. In the simplest terms, this cementitious material is composed of fly ash, Portland cement, hydrated lime, water and a small amount of aluminum paste that, through the use of physical processes and manipulations, form a cellular solid material of varying density. By physically manipulating the material during casting, I have found that one can control the density of the material, for example locating denser material on the surfaces of a cast block while maintaining a lightweight cellular structure on the interior of the block. Unlike traditional composites, where materials of differing properties are assembled together to achieve a higher-performing amalgam, this material is produced in such a way that it can have integral density gradients that provide a smooth transition from one extreme to another. This new material is defined by its inherent variability. The chemical composition is not novel. What is novel are the macro-level compositions that can be produced using the methods developed during the course of this research program.

The invention is significant because it opens up the possibility for the production of more sophisticated manufactured materials for use in the built environment. This is a model largely based on structures and materials found in nature–materials that are highly efficient in terms of material usage versus function. By thinking about construction materials in a similar way, one can achieve great improvements in the design of buildings. With this research, I have tackled the goal of creating materials that are highly optimized for a given function by rethinking the way materials are produced. The ability to make this variable property material is based in a method for affecting a cast material as it is being formed. I use processes that influence and control a resultant material. Instead of "assembling" a material, I manipulate it to produce something entirely different. This falls under the category of many processed materials made in this manner. For example, forged metals are manipulated so that they become stronger and more ductile on a molecular scale. On a macro scale, layers of metal are forced into alignment so that something such as a blade becomes much sharper and more durable–both critical performance characteristics for a cutting tool.

My efforts over the course of this research program to produce variable property concrete have resulted in the development of a suite of methods for affecting the material as it is being produced (Table 1.2.1). All of these processes are conducted immediately after constituent materials have been mixed and during the initial forming of the material when the internal cellular structure is being established. Through the use of these methods, one can hypothetically control the density at any location in a cast object. This is achieved through the regulation of the chemical aeration of the material during its initial setting in the first few hours after the material is poured. The following table lists the various methods and gives a brief description of each.

Table 1.2.1
A list of methods for affecting the internal cellular composition of aerated concrete

Method	Description
Gravity Casting	The characteristic vertical variation in hydrostatic pressure found in fluids at rest results in an increased density as one moves lower within an element cast out of aerated concrete. The increased pressures associated with taller columns of liquid result in higher density material at the lower bounds of aerated concrete castings.
Rotational Casting	By rotating a concrete slurry as it chemically aerates, one can generate fluid pressures that vary radially, opening up the possibility for radial density gradients.
Permeable Formwork	Through the use of permeable formwork, one can remove water from the near-surface regions of a casting, resulting in a reduction in the water/cement ratio in those regions. Experimentation has demonstrated that reduced water/cement ratios result in increased densities when casting chemically aerated concrete.
Absorptive Formwork	Absorptive formwork also serves to reduce water/cement ratios near the surfaces of castings, allowing one to control the density based on the absorptive properties of the casting material.
Mechanical Agitation	By mechanically agitating the cellular matrix of air-voids immediately following the aeration process, one can densify isolated regions of a cast element, opening up the potential for the creation of densified regions on the interior of aerated concrete geometries.

Concrete is an inherently heterogeneous material that modern industry has tried to make homogeneous. This research accepts the material's tendency for variation, capitalizing on this macro-level heterogeneity in an effort to produce a construction material whose properties can be varied based on the needs of a specific part of a building. By considering internal material distribution, one's ability to imagine more sophisticated construction materials is vastly enhanced. Also, if one can imagine a casting process by which this internal material composition is created through manipulation of that material without the need for assembly and the multi-step process it implies, the production model for a cast material remains as simple as the production model for uniform property cast materials.

The most obvious and direct application for the variable density concrete that has been developed during the course of this thesis would be within the structural precast concrete industry. Precast concrete beams, columns, panels and blocks that contained internal density variation could be deployed as replacements for many of the standard precast concrete components used in buildings today, opening up the possibility for significant material usage reductions and more structurally efficient building components. For example, I was able to reduce by 28 percent the material used in a variable density beam prototype (Chapter 5) without reducing its capacity to resist bending. Though this research did not explore tensile reinforcing used in conjunction with variable density, the vast improvements possible in strength-to-weight efficiency are only exciting if one considers the strategic inclusion of bar or fiber reinforcing within the context of variable density concrete.

1.3
Thesis Outline

The larger context within which this work is situated is described in Chapter 2. In this chapter, I detail how I am looking at the production of materials for human consumption. I am particularly interested in comparing the ways in which materials are processed, whether through industrial production or craft traditions. I believe there is value in taking lessons from non-industrial methods for processing materials and applying these models in an effort to improve how we produce modern-day construction materials. In this chapter I also talk generally about how we categorize materials and describe in detail the specific class of materials called cellular solids. Cellular solids are an important class of material. Found extensively in nature, they have been used by humans for thousands of years.

Chapter 3 focuses on the history, science and mechanics of autoclaved and non-autoclaved aerated concrete, which are lightweight concretes that are characterized as cellular solids. This chapter concludes with a description of what I see as the need and opportunity within this material type for innovation and development.

Chapter 4 describes the theoretical and methodological principles that have guided this work. I discuss the challenges and opportunities that arise when a designer engages in an applied research program. To provide context, some examples of this type of work are discussed. The final section in Chapter 3 outlines the constraints and goals I have established as I developed this research agenda.

Chapter 5 provides a detailed description of the experimental work that was conducted during the course of this project. This chapter constitutes the core of the work and serves the double purpose of informing the reader about the products of the work while also providing an understanding of my experimental practices and decision-making process.

Chapter 6 serves to sum up the work and provides a space for reflection on the potential implications of this work. Ongoing work and the potential for future work are also summarized.

Chapter 2: Background

In this chapter, I frame my work with aerated cellular concrete within the context of engineered building materials, and more broadly, discuss the ways in which humans have manipulated and processed materials for their everyday use, from clothing to buildings. I contrast the constraints and benefits inherent in industrially produced construction materials with the flexibility and potential for advancement when looking to alternative models for the production of construction materials. In the second section of the chapter, I look more closely at synthetic and naturally occurring cellular solids, highlighting the difference between these two manifestations of this type of material.

2.1
Processed Materials

Transformation through manipulation

We have always used materials to serve our needs. This utilization of materials is one of the main attributes of human activity that distinguish our species. We exhibit an astounding ability to appropriate naturally occurring materials and put them to use as shelter, clothing, food, storage, weaponry and of course–a most uniquely human endeavor–as art. Most critically though, humans would not be able to survive without the shelter we make out of these materials–in the form of clothing and buildings. What interests me within the context of my research in variable density cellular concrete, are the diverse and powerful methods humans have developed to manipulate and process natural materials all in an effort to transform them into products that are valuable for human consumption and use.

For most of human history and prior to the industrial revolution and the mechanization of production, we manipulated materials by hand to change their composition and intrinsic properties. There are countless elegant examples of this manipulation, but I will only mention a few to illustrate this relationship to materials. One of the closest relationships we have is with natural fibers, both plant and animal. We have harvested natural fibers for millennia–mainly for use as clothing. The fiber we might extract from the bark of a cedar tree or off the back of a sheep is usually not in a state that is very useful for our purposes. These fibers must be processed so that we can turn them into durable and protective textiles. Traditionally, plant fibers must be soaked or boiled in water to increase their malleability and reduce their vulnerability to fracture when used to weave textiles or basketry. Another common way to prepare natural fibers is to work the raw material physically with mallets or by hand to break up the fibrous material and allow for its re-composition into ropes or threads. In both cases, the material is being manipulated (in the former via the application of heat energy and/or water and in the latter through the application of kinetic energy in the form of physically applied force) to alter the intrinsic properties of the fibers.

In the case of animal fibers, the process of felting is a timeless example of humans manipulating a material to drastically change its form and properties. Felting is an ancient technique that developed after humans began domesticating animals (Crawfurd 1863, 398). The earliest evidence of its use dates back 8,500 years (Burkett 1977, 112). Felting is a process by which animal fiber, most commonly wool, is compressed and worked in the presence of moisture, and sometimes heat, binding the individual fibers together and creating an incredibly durable and strong non-woven cloth. In essence, felt is simply entangled animal fibers, matted together (Mullins 2009). Felting is interesting, not only because it is one of the most basic and ancient ways of processing fibers, but also because it is a perfect example of the type of processed materials I am interested in. Fibers can be woven and knitted, but it is the act of felting that most exemplifies what I'm calling "material manipulation" in the context of my research. To weave or knit fibers, one is solely organizing a given substance in a particular configuration, but with felting, as with other material manipulations I will discuss, the material itself has been changed in order to allow one to create the final product.

Material manipulation is a general term that can mean many different things. I am interested in defining material manipulation as it relates to scale. If one is manipulating a material at the atomic scale, then one could say the chemical composition of the material is being altered. At the micro scale, a material manipulation might involve the rearrangement of cells or crystalline structures, resulting in an altering of the microstructure of that material. At the macro scale, material manipulation might mean the rearranging of parts, such as the rearrangement of wool fibers during the felting process that results in a macro scale transformation of the material. In all of these cases, no matter the scale, what interests me is how the manipulation is being produced. There is a danger that this way of describing the processing of materials could become too general and lose its meaning; my intention when using this term is to differentiate what I am advocating from the idea of the assembly of materials to achieve a given function.

To be more precise, I am using the term "material manipulation" to encompass any method for processing materials where the internal composition or the microstructure of the material is altered, resulting in a macroscopic behavioral change in the material. If one is discussing this within the context of engineered materials, the definition of engineered materials is basically predicated on some sort of processing or "manipulation." But a huge portion of the material processing techniques used can be either grouped under the category of formal and geometrical transformations or basic chemical transformations. Much of the time raw materials are processed in order to produce a specific shape. These processes can either be additive or subtractive: polymers and metals can be cast or extruded into desired shapes; wood is sawn into prismatic shapes. I am interested in the type of manipulation that results not necessarily in a change in shape. Equally, I am not interested in manipulations that solely change the chemistry of a material. Instead, I am interested in manipulations that produce a change in material composition. Sometimes the act of shaping a material might produce changes in the internal composition. This is the case for many of the methods for processing materials that have stood the test of time (for example, the forging of metals and traditional ceramic-making methods).

The classic example of the manipulation of a material to change its properties is metallurgy and the forging of metals. Through simple processes, metals can be shaped, heat-treated, surface-treated, and combined to create alloys. All of these processes dramatically transform the raw materials. By heating and working metals, the make-up of the material can be changed at an atomic scale, a micro-scale, as well as the macro-scale. At the atomic level, carbon might be driven out, increasing the ductility and strength of the material. At the micro-level, the material can be drawn out or compressed to orient the internal gain of the metal's crystalline structure (Figure 2.1.1). This ability to dictate the way the grain is composed allows one to increase the strength of a particular piece of forged metal (DeGarmo 2003, 392). At the macro level, metals with different properties can be layered and worked together to form integral structures that, though the combination of multiple types of metals, provide great strength and stiffness while also remaining ductile. Most importantly though, I want to emphasize the fact that the process of forging metals is used to create the macro-level form of the material while at the same time organizing the internal composition of that material. This is the type of "material manipulation" model that inspires the work that I am doing.

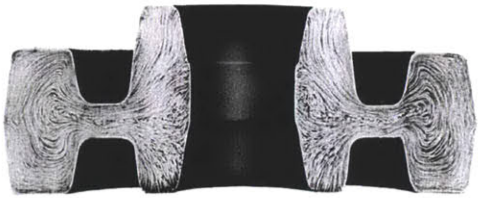


Figure 2.1.1
Flow structure of a hot-formed (forged) transmission gear blank. (DeGarmo 2003, 374)

To give another example of the type of "material manipulation" where form *and* internal composition are determined through a single process, I will briefly describe the material transformations that occur when a potter hand builds or throws a clay pot. Clay, a hydrated aluminum silicate, is a plastic material when it is in its natural condition. It is a mineral with a crystalline structure that originates from decomposed igneous rock. Most clays used to make stoneware (stoneware is commonly used to make ceramic housewares) is a variable and responsive material, containing clay particles of varying size. The laminar kaolinite crystals that clay is composed of are generally flat and hexagonal in shape. When they are compressed during the throwing or hand-forming of a pot the crystals orient perpendicular to the direction of compressive force (Hamer and Hamer 2004). By orienting the crystalline structure of the material in this way, the piece is strengthened and bolstered against shrinkage cracking that occurs when the clay dries and is fired (Figure 2.1.2). It is through this reorganization of the internal

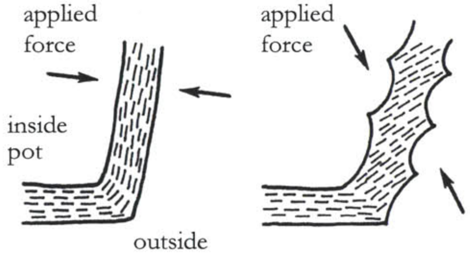


Figure 2.1.2
Clay particles orient perpendicular to applied pressure. Diagrammatic illustration not to scale. (After Hammer and Hammer 2004, 67)

composition of the material that the production of ceramics has remained one of the basic technologies essential throughout much of human history. This age-old practice is an elegant example of a material manipulation where through a single action–the simple act of throwing a pot–the macro-level shape of the material is determined as well as the internal composition.

A discussion of the ubiquitous materials used throughout human history must include mention of wood. Wood is highly anisotropic, meaning that the material properties of wood are highly dependent on the axis of measurement relative to the orientation of the grain. Most fundamentally, wood is much stronger when resisting forces acting along its grain than across its grain. As well, the shrinkage and resultant cracking of the material due to drying is highly dependent on grain orientation. Humans have been manipulating wood for centuries in order to exploit and manage this anisotropic structure. By the simple act of orientation, the same species of wood can be used for diverse purposes. When it comes to the manipulation of wood, what most fascinates me are the long traditions of bending and laminating. By treating wood, either chemically or through the use of heat or steam, the relatively brittle and stiff material can be radically transformed. When combined with lamination–the gluing of multiple layers of material together–processed wood can be used to create amazingly diverse forms and structures. The long tradition of treating and bending wood (mostly related to boat building throughout history) began being exploited in the production of mass-produced furniture in the first half of the twentieth century when designers such as Alvar Aalto, Eero Saarinen and Charles Eames combined new laminated wood technology (plywood) with bending techniques to create molded plywood furniture (Griffith Winton 2007). This new way of manipulating wood precipitated a revolution in how wood is utilized in industrial design and construction.

Material production in the industrial age

With the introduction of industrial production processes in the 19th century, our ability to manipulate and manufacture materials drastically changed. Mechanization vastly increased efficiency and productivity, but to the detriment of flexibility and customization. The imperative of industrial production was standardization. Industrially produced materials are homogeneous and uniform by necessity and design. But with this standardization comes limitations. For example, the vast majority of industrial production processes utilize either concepts of extrusion or assembly, thus resulting in the dominance of the "stick" and "sheet" as two of the most common morphologies that make up our physical environment.

One of the main alternatives to these two common types of production is the casting process. My research is founded on the belief that the use of the casting of materials as a production mode is the ripest for innovation and advancement. It is true, for example, that cast concrete is the most common construction material used today, but the possibilities that I believe casting offers are constrained by the "sheets" and "sticks" we typically use as the formwork for our cast concrete structures. There are great examples of innovative uses of cast materials in buildings over the last century, for example the reinforced thin-shell concrete structures of Pier Luigi Nervi and Felix Candela, but these remarkable uses of cast materials are certainly not the norm.

This thesis contends that casting is the type of material production that has the greatest potential to advance how we produce materials for the built environment. What if, like the throwing of clay and the forging of metals, casting as a production process could dictate not only the form of a material, but its internal composition? This contention will be expanded upon in later chapters, but for now it is important to emphasize that the usual imperative of industrial production is the creation of a homogeneous material. My research is concerned with taking lessons from some of these age-old ways of processing materials in an effort to produce engineered materials that have controlled heterogeneity. Specifically, I am interested in approaching the production of cast concrete with some of these basic material manipulations in mind. Based on my research, I have found that the key to expanding casting's capabilities as a production model is to exploit

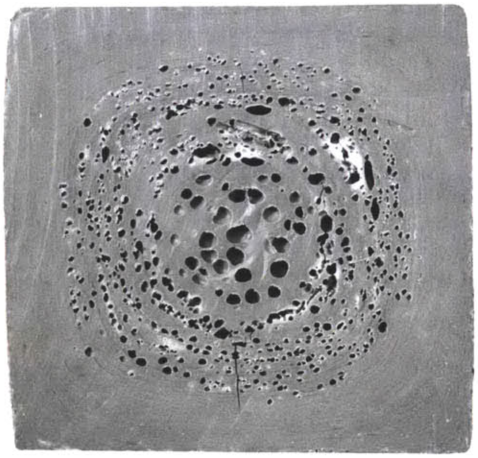


Figure 2.1.3
Cross-section of an injection-molded structural foam component displaying an aerated cellular interior and an integral solid plastic shell.

the interaction between the material being cast and the formwork. A production model for casting materials needs to go beyond the idea that formwork solely determines geometry. The interaction between formwork and the molded material can determine material properties and dictate internal composition.

A good example of a molding processes being used to do just this is the injection molding method used to make structural foam: the strategic manipulation of heat energy and aeration during the injection process results in a molded plastic that has a lightweight aerated interior and a strong and dense surface. This type of injection-molded plastic is used extensively to make durable yet lightweight products such as shipping pallets and storage containers (Figure 2.1.3).

Another interesting example of the molding process being employed beyond external shape control is the practice of casting technical ceramics in sacrificial foam substrates. An open-celled polymer foam is soaked in a ceramic slurry. The foam soaks up the porcelain, impregnating it. It is then fired and the foam material is completely burned out of the "casting", leaving a porous ceramic that has not only taken macro-scale shape of the foam but also the micro-structural shape of the foam pores (Lange and Miller 1987). These porous ceramics can serve for example as filtration devices and catalyst supports (Williams and Evans 1996).

The relatively low performance inherent in a homogeneous material has not been lost on modern engineering. More and more there is a push to create more sophisticated materials with variable properties using new production techniques and new materials. By combining materials with widely divergent properties, amazingly efficient and effective materials can be created. The classic example is reinforced concrete. By combining material with high compressive strength (concrete) with a material such as steel with its high tensile strength, a higher performing composite material can be produced. This model, based on combining materials to gain a composite that is higher performing has been employed widely in modern industrial material production, from fiber-reinforced polymers such as fiberglass and carbon-fiber-reinforced plastics

(CFRP) to common engineered wood products such as plywood.

It is interesting to note though, that the variability in natural materials such as wood has been something that modern industrial processing techniques have traditionally tried to mitigate. As a result, we have for example developed engineered wood products with the aim of reducing the variability inherent in this common natural material. Plywood, oriented strand board, glued laminated timber, and laminated veneer lumber are all examples of wood products that have been developed to create a more homogeneous and predictable material for use in engineering applications.

These impulses to create more predictable engineering materials have had huge positive repercussions and have greatly expanded our capacity as humans to build with ease and efficiency. On the other hand, if we want to take the next step and create controlled variability within our engineered materials, I contend that there is an underlying conflict when it comes to producing a heterogeneous material using existing industrial production. Instead of trying to create uniform materials–composites or otherwise–the new imperative as I see it is to be able produce materials with variation in internal composition, and the challenge lies in finding new production practices that facilitate this new mandate.

2.2
Cellular Solids

Engineering materials can generally be categorized into four broad classes: metals, ceramics, polymers and composites. A separate and less specific material type that overlays this classification system is biological materials, which encompasses materials created by living organisms (for example, animal and plant fibers). Cellular solids are typically considered a type of composite–most commonly a combination of air and a solid material. The solid fraction of a cellular solid can be composed of any of the five classes of materials. Metals, ceramics, and polymers can all be distributed to create cellular structures. In addition, examples of

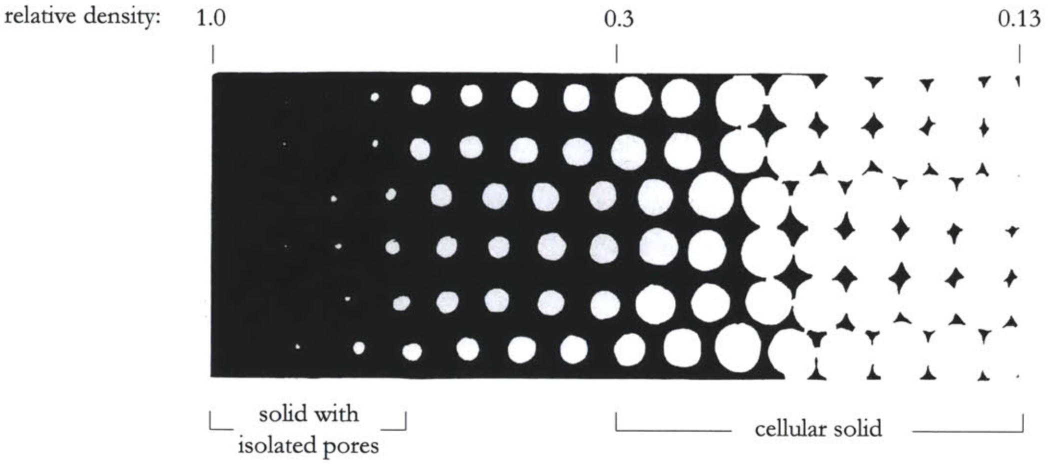


Figure 2.2.1
A gradation of porosity, with the division between a solid with isolated pores and a cellular solid indicated

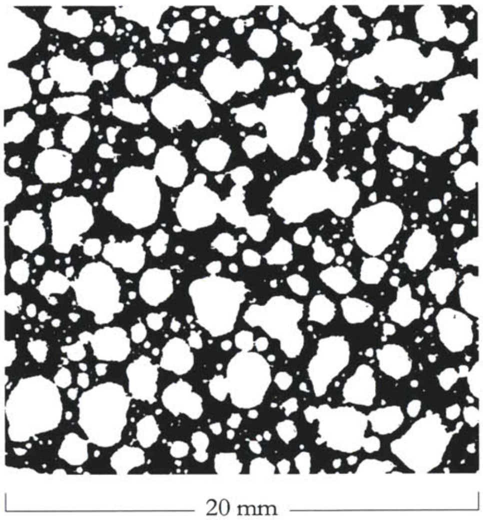
biological cellular solids abound in both the plant and animal kingdom.

Cellular solids are identified by a particularly organized distribution of material. These materials are characterized by a distribution of material that results in discretized compartments delineated by thin walls or separated by columnar structures or struts. The cells that are formed may be open to adjacent cells or closed. There are three general morphological categories: two-dimensional honeycomb structures, three-dimensional foams with open cells, and three-dimensional foams with closed cells (Gibson and Ashby 1997). Each of these general types of cellular solids display distinct material properties. By foaming a solid material and creating these types of internal structures, engineers can regulate material properties such a density, conductivity, young's modulus (stiffness), and strength. All of these material properties are of course dependent on material properties of the base material being foamed, but with the introduction of a cellular matrix, the range in performance of a material can be vastly increased. By changing such cell parameters as size, shape and distribution, the material properties can be controlled, but the most important parameter that indicates what the material properties of a particular cellular solid will be is its relative density. Relative density, (ρ^*/ρ_s), is the density of the cellular material (ρ^*) divided by the density of the solid material (ρ_s) from which it is made. In general, solids are considered a cellular solid when they have a relative density less than 0.3 (Gibson and Ashby 1997). Figure 2.2.1 illustrates this dividing line between what is considered a solid with isolated pores and what is considered a cellular solid.

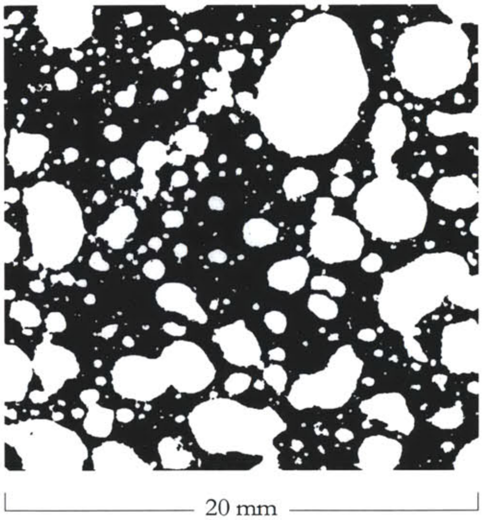
To reiterate, relative density is the most important factor in determining the mechanical and thermal properties of cellular solids. Cell shape, and to a lesser extent cell size, are also important predictors of the material's properties, but for my work, I concentrated mainly on density and did not delve deeply into the characterization of the cellular structure beyond a qualitative comparison of the cellular structures I produced. In general, I tried to produce the least amount of cell size variation at any particular location within my castings. I was also interested in creating closed cell structures due to the increased thermal resistivity closed cells provide. Even though I was trying to create wide variation in density within the material, at a local level my goal was to create as homogeneous a material as possible. Figure 2.2.2 shows two extreme examples of the types of cellular structures I produced over the course of my experimental work. The more desirable structure would be the first, more uniform sample. This is because it has been established that a more uniform cell size in aerated concrete yields greater strength (Nambiar and Ramamurthy 2007).

Figure 2.2.2
Two thresholded images of cellular structures

(a) relatively homogeneous composition



(b) relatively heterogeneous composition



Biological cellular solids

Some of the most interesting cellular solids are those found in nature. Living organisms are very adept at creating cellular structures to suit their needs. By regulating the cellular composition of a material, organisms can control material properties. In biological organisms, cellular matrices serve as structural scaffolding, circulatory and capillary conduits, impact and shock resistance, and volume filler among myriad other purposes. Flora and fauna use cellular structures as integral elements, including their bones, wings, skin, stems, leaves, and exoskeletons. These cellular structures are frequently non-uniform, their composition often changing depending on the particular requirements at a given location. Whether to add strength, provide greater cushioning and shock resistance, or to minimize the amount of material invested by the organism, biological structures are often exquisitely tuned to place only

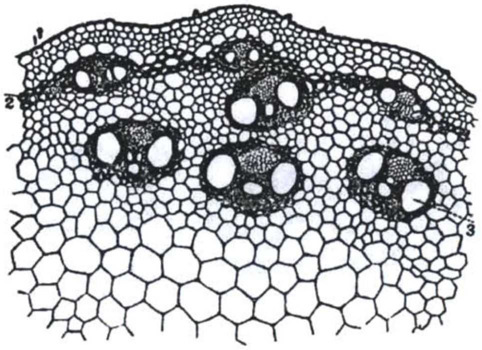


Figure 2.2.3
A detail illustration of a portion of the stem of *Panicum Isachne* showing the radial variation in the cellular composition of the plant.
1. Epidermis; 2. sclerenchyma; 3. vascular bundle. (Rangachari and Mudaliyar 1921)

the necessary amount of material in the precise location in which it is needed.

These non-uniform distributions of material commonly found in natural cellular structures fall into two general morphological categories: the sandwich panel and the radial gradient. In both cases, material is distributed in such a way that stiffness and resistance to buckling are optimized while weight is minimized. The separation of a stiffer and stronger material to the faces of a sandwich structure that is filled with a lighter-weight cellular core increases the moment of inertia of the composite while at the same time minimizing any increase in weight. This means that sandwich structures are most often associated with plants and animal structures that need to be lightweight yet stiff, such as the leaves and stalks of grasses or the skulls of birds. In larger birds such as owls, the skull is composed of multiple stacked sandwich panels. As well, the shells of some arthropods, such as horseshoe crabs, are sandwich panels. The mechanical properties of these types of structures are governed by the material properties of the core and skin material as well as the overall geometry of the panel.

Radial gradient structures are commonly found in the stems of plants. Animal quills (e.g., the quills of a Blue Jay's feathers, porcupine quills) and some beaks of large birds (e.g. Toucan, Hornbill) also have integral radial density gradients. In plant stems, the outer shell is often composed of denser sclerenchyma fibers while the stem cores often have honeycomb-like or parenchyma cells (Figure 2.2.3). Like sandwich panel structures, a radially distributed gradient maximizes stiffness and buckling resistance while minimizing weight (Gibson and Ashby 1997).

Wood (*materia* is Latin for wood, specifically referring to the trunk of a tree) is a particularly abundant example of a naturally occurring cellular solid. As with most cellular solids, wood's material properties depend of relative density, and are anisotropic. Wood comes in amazingly diverse forms, with relative densities (ρ^*/ρ_s) that range from as low as 0.05 for balsa to 0.80 for *lignum vitae* (Gibson and Ashby 1997, 390).

Synthetic cellular solids

In contrast to biological cellular solids, manmade cellular solids are generally not as sophisticated as those found in nature in that we don't generally have the ability to internally vary cellular structures to respond to variations in performance criteria. Despite the fact that the subtle variation in structure found in natural foams has yet to be fully realized in their synthetic counterparts, the development of synthetic cellular solids has been a longstanding area for modern materials research. The functional attributes and performance targets for synthetic cellular solids mimic those of their natural counterparts: greater thermal resistance and shock absorption, volume filler, weight reduction, greater stiffness and overall toughness, among many others.

Synthetic cellular solids have played diverse roles in many components for buildings, including insulation materials, sealants, spacers, environmental barriers, and heat exchangers. Despite the similarities in the performance targets for synthetic and biological cellular structures, synthetic foams are rarely engineered for variable density. More often a critical material development goal for synthetic foams is homogeneity and consistency of density. The research I have conducted is an attempt at achieving the opposite. My goal is to be able to produce controlled variation in the density of cellular concrete. By controlling the distribution of density within a building component, and as a consequence the distribution of material, great possibilities for drastic improvements in the efficient use of these materials are possible.

Figure 2.2.4
A cross-section of a human tibia. Like most bones, the outer shell is an almost fully dense *compact* bone that encloses a core of porous cellular, *cancellous*, or *trabecular* bone.
(By permission: Gibson 1997, 429)

Chapter 3: Autoclaved and Non-Autoclaved Aerated Concrete

This chapter describes aerated concretes and their use in the construction industry. The first section provides some background for aerated concrete use within the broader context of the concrete industry. In the second section, aerated concretes are defined. In addition, the history and development of the material over the last century along with details on how AAC is typically produced are outlined. In Section 3.3, I discuss in detail the science and material properties of autoclaved aerated concrete (AAC) and non-autoclaved aerated concrete (NAAC) and review the current state-of-the art within the industry. I conclude by describing what I see as the need within the industry and outlining my own approach for contributing to the field of aerated concrete research and the concrete industry as a whole.

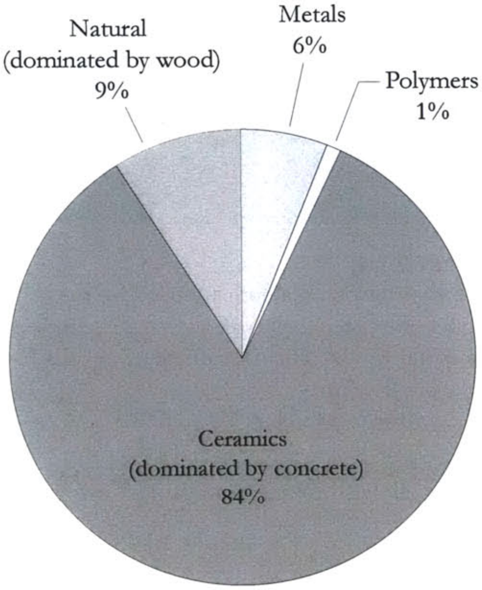


Figure 3.1.1
Material usage measured by weight (after Ashby 2009)

3.1
Concrete and the Built Environment

Over the last century and a half advances and breakthroughs have greatly expanded the application and use of concrete in construction. Through scientific research drastic improvements in the micromechanical properties of concrete have been made, from increasing its ultimate strength to improving workability and shortened curing time through the use of synthetic additives. The invention of pre- and post-tensioning methods as well as the use of high strength polymer fiber reinforcement have also produced great benefits, allowing the material to be used in ever more efficient and high performance applications. But there remains much room for further innovation and improvement in the field of concrete research.

Currently, concrete is the most abundant of all manufactured solid materials on the planet (van Oss 2005). Figure 3.1.1 provides some perspective on the magnitude of concrete consumption compared to the other material families. Our consumption of concrete is higher, when measured in terms of tons per year, than our consumption of oil and coal (Ashby 2009, 17), and is only second to water when one considers all natural resources humans consume. The manufacture of Portland cement, one of the main constituent components of concrete, is an energy intensive process and significantly contributes to greenhouse gas emissions.

In fact, Portland cement production, depending on the source, has been calculated to account for up to 8% of all anthropogenic CO^2 emissions (Müller and Harnisch 2008). In light of concrete's huge share of anthropogenic CO^2 emissions and its ubiquity as a construction material, there is a great need for developing more environmentally sustainable concrete. Because impact scales with quantity of material consumed, by creating better concrete, there is great potential for significantly reducing the impact the built environment has on our planet.

Efforts to reduce the environmental impact of concrete can be grouped into two categories. 1) Developing methods for more efficiently utilizing the material. This can be achieved by designing more efficient structures so as to reduce the quantity of material required for a given function. 2) Reducing the embodied energy of concrete, for example by replacing energy-intensive component materials such as Portland cement with lower embodied energy substitutes such as fly ash, a coal-fired power plant byproduct. The first strategy can generally be characterized as *dematerialization*, while the second strategy can be described as one of *reducing the embodied energy* of the concrete we do end up using in our buildings. Overlaid on top of these two strategies for reducing the impact of the material itself, is the impact buildings made from the material have in terms of the energy used in the operation over the lifetime of the building. This is an important component of the picture because the energy used in operation of our built infrastructure is a huge share of global energy consumption. If we can reduce the environmental impact of concrete by using less material for a given function (*dematerialization*), improve the manufacturing methods (*reducing embodied energy*), *and* create more energy efficient buildings at the same time, one can imagine a complete picture for improving this most common building material.

3.2
Overview and History of Aerated Concrete

One type of concrete that starts to address some of these issues falls under the general category of lightweight concrete. There is a wide range of types and classes of lightweight concrete, from aerated to lightweight aggregate concrete. Each have specific applications, from structural members to non-structural infill material, but the most widely used is Autoclaved Aerated Concrete (AAC). In general terms, lightweight concrete provides opportunities within design and construction to more widely deploy cementitious materials for use in the built environment. All lightweight concretes can be generally categorized as cellular solids. As we know from the earlier discussion of cellular solids in Chapter 2, by foaming a solid material, and thus creating a cellular solid, we can expand the range of properties possible for the material (e.g. thermal conductivity, stiffness and strength, etc.). This is why lightweight concretes are an exciting class of cementitious material; one is able to increase the range of applications and uses for the material, allowing for more appropriate and efficient material usage. Through cellularization of the solid form of concrete, we have at our disposal a material whose properties can be tailored to a greater extent.

On a basic level, if we can reduce the density of concrete by transforming it into a cellular solid, we are able to reduce the amount of material used to produce a given geometry. When one considers this method for reducing material usage for a given geometry, one needs to take into account the material properties that change through this sort of *dematerialization*. Two of the most important relationships are the reduction in strength as density is lowered and reduction in thermal conductivity of the material with lowered densities. These two key relationships will be discussed in greater detail in Section 3.3.

In a broad sense, lightweight concrete refers to concrete that has a density lower than 2000 kg/m^3. By comparison, normal density structural concrete made with natural stone aggregate typically has densities ranging from 2242 kg/m^3 to 2434 kg/m^3 (Nilson et al.

2004, 30). There are two general types of lightweight concrete: lightweight aggregate concrete and aerated concrete. Lightweight aggregate concrete, depending on its density, can be used as a structural material at higher densities or for insulating and infill applications at lower densities. It can be made with unprocessed aggregates such as pumice, but more commonly it is made with processed aggregates such as expanded shales and slates. Synthetic aggregates such as expanded polystyrene can also be used to create lightweight aggregate concrete (Chen and Liu 2004). My work has been solely concerned with aerated concrete, and as a result the following overview is restricted to aerated concrete.

To quote Narayanan and Ramamurthy's concise review of the structure and properties of aerated concrete (2000), "aerated concrete is either a cement or lime mortar, classified as lightweight concrete, in which air-voids are entrapped in the mortar matrix by means of a suitable aerating agent." Aerated concrete can be produced in a wide range of densities, from as low as 300 kg/m^3 up to 1800 kg/m^3, but for aerated concrete to be considered a true cellular solid, as defined by Gibson and Ashby, it must have a relative density less than 0.3 (1997). Therefore, one must generally confine one's definition of aerated cellular concrete to be concrete with densities lower than around 800 kg/m^3 depending on the density of the non-aerated solid from which the concrete is made.

There is some amount of ambiguity when it comes to the terminology used to describe aerated concrete. For example, because, strictly speaking, aerated concrete refers to a cement or lime mortar that contains a matrix or air-voids and no large aggregate or course sand, aerated concrete could just as easily be called *aerated cement*, *cellular cement*, or *aerated mortar*. In 1954 Valore, who wrote the first comprehensive review of aerated concrete, listed terms such as "porous concretes," "foam concretes," "foamed concretes," "gas concrete," and "aerated concretes," to give a few of the generic terms associated with this material. For my purposes, because I am interested in aerated concrete as a structural material, I will adhere to current convention and refer to it as "aerated concrete."

Aerated concrete can refer to a number of different types of cellular concretes composed of a matrix of air-voids within a cementitious solid. Aerated concrete can be classified based on the method of pore-formation, based on the type of binder used, or based on the method of curing. Table 3.2.1 lists the three systems for classifying the material and provides a brief description of the methods grouped under each classification heading.

Table 3.2.1
Three ways of classifying aerated concretes: based on method of pore-formation, method of curing and type of binder (based on descriptions found in Narayanan and Ramamurthy 2000)

1. Method of pore-formation	2. Method of curing	3. Type of binder
Chemical aeration: pores are generated when a chemical additive, most commonly aluminum powder, is combined with the cement or lime mortar during its fluid or plastic stage. The additive chemically reacts with the alkaline mixture, generating gas bubbles that create the porous structure. Other names for this method include *air-entrained concrete* and *gas concrete.*	**Autoclaved:** for this curing method, aerated concrete is steam cured in autoclaves that subject the material to high pressures (4-16 MPa) and temperatures for periods of time ranging from 8 to 16 hours. This method allows for shorter curing times, increased strength and reduced drying shrinkage.	Aerated concrete can be made by using either **Cement** or **Lime** as the binder.
Mechanical aeration: pores are introduced mechanically either by adding a preformed foaming agent or directly adding a foaming agent to the mortar. This method does not rely on chemical reactions for the formation of pores. Agents used include detergents, resins, soaps, glue resins, and hydrolyzed proteins such as keratin. Other names for this method include *foam concrete* and *foamed concrete.*	**Non-Autoclaved:** for this curing method, aerated concrete is moist-cured at room temperatures and under normal atmospheric pressures. Strength develops slowly and drying shrinkage is a major concern.	**Pozzolanic materials** such as fly ash or slate waste can be used as partial binder or filler replacements.

History

Patents for producing aerated cementitious and lime mixtures date as far back as 1889, but it was not until 1914 that a patent was filed which described the use of aluminum or other powdered metals to create aerated cementitious mixtures (Valore 1954, 774). It was the addition of autoclaving, invented by the Swedish architect Johan Axel Eriksson in 1924, which precipitated the wide adoption of the material for use in buildings (Matthys and Barnett 2004). In response to the energy crisis and the shortage of wood in Sweden at the time, the development of an autoclaved aerated concrete provided an alternative building material that could compete with wood and also permit the creation of more energy efficient buildings. Eriksson is said to have accidentally stumbled upon the process. He wanted to speed up the curing process and so he put a few samples of aerated cement in an autoclave. Not only did the autoclaving speed up the curing, the high pressure and temperature environment of the autoclave produced a crystalline cellular material that had drastically increased strength and stability over any previously produced aerated cementitious material. In many ways, the material he had invented was a man-made version of lightweight volcanic minerals such as pumice and scoria that have been used as building materials for thousands of years. In actuality, he had discovered how to produce a specific type of calcium silicate hydrate with a strong crystalline structure called Tobermorite.

Because of its cellular structure, aerated concretes behave differently than most other solid ceramic materials. The cellular matrix allows the material to better absorb impact energy. It is because of this that aerated concretes can be worked in many ways much like the wood products it was intended to replace. It can be dry-cut using carbide tipped saw blades used in typical woodcutting saws such as bandsaws and circular saws. Also, the material accepts fasteners such as common nails and screws because brittle fracture is not generally a concern and the composite of air and cementitious material is soft enough for one to easily hammer or screw into.

By 1928, the material Eriksson had invented had been licensed for production by the Swedish building material producer Karl August Carlen. The insulating masonry material quickly gained popularity in Europe (Hellers and Schmidt 2011). It continues to be used widely in Europe and many parts of Asia, including India, Japan and China. There are now over 300 producers of AAC worldwide. Xella International GmbH is currently the largest producer of AAC.

Despite its prevalence in numerous markets around the world, AAC has never gained a sizable market share in the US. There are a number of factors that have contributed to this, but the most commonly cited reasons for its slow adoption in the US building market include the entrenched light frame wood construction industry that serves the single- and multi-family housing market and the lack of institutional and governmental incentives to use energy efficient materials.

European companies such as Hebel (which was bought by Xella in 2002) and Xella have built plants in the US over the past few decades, but currently there remains only one active producer of AAC in the US, Aercon AAC located in Haines City, Florida. Despite the closing of production facilities over the last few years in New Mexico and Georgia, at the time of this writing a new production facility is slated to start producing AAC in North Carolina (carolinaaac.com) and capital is being raised for a planned facility in Colorado (Alexander 2012).

Another factor that has contributed to the failure of many of the plants that have been opened in the US in the last few decades has been a problem of distribution. The production models that the US plants adopted were designed based on markets and geographies typical of a European context. European countries are geographically much smaller and have denser populations than the US. Because of this, large production facilities are the norm. A single plant can easily serve an entire region or even an entire country. When these same European manufacturers came to the US, they applied this model, building large plants that were intended to serve a region. In the US though, the costs of distribution associated with interstate shipping made the material non-competitive with established construction materials such as wood. This fact, combined with the difficulties of getting a building industry to use a new material, have hampered the expansion of AAC usage in the US.

In light of this, I propose a different production model based on smaller, more flexible plants that serve local markets. This would solve the distribution problem and also reduce the startup costs and investment required for an individual plant, thus reducing and distributing the risk associated with capital investment in a new product. This seems to be the model being adopted by the new Carolina AAC manufacturing plant. It uses Wehrhahn "Smart Plant Technology" from Germany and is designed to initially be able to produce 3.6 million cubic feet (~102,000 m^3) of product per year with the ability to expand in the future (Weems 2012). This is a relatively small plant compared to European standards. By comparison, one of the largest European production plants located in Solec Kujawski, Poland has a daily production capacity of 2,300 m^3 (Solbet company brochure), or roughly six times the capacity of the new plant in North Carolina.

How Aerated Concrete is Produced

As has been summarized in Table 3.2.1, aerated concrete can either be autoclaved or moist cured, mechanically or chemically aerated, and can be composed of various raw materials. Because AAC that has been chemically aerated (usually with aluminum) is by far the most widely used class of aerated concrete, I will describe how it is produced in detail and then compare this production model to non-autoclaved aerated concrete. There are subtle differences in the resultant material depending on the method of aeration and the types of binders used, but the most critical determinant of material properties and environmental impact is whether or not the aerated concrete has been autoclaved (Valore 1954, 775). It is because of this fact that I have chosen to compare autoclaved and non-autoclaved aerated concrete here.

(Note: Preference for classifying aerated concretes based on method of curing was proposed by Valore back in 1954. His authoritative and comprehensive review of aerated concrete is relied upon in the literature to this day.)

Autoclaved aerated concrete is made from the combination of a binder material (cement or lime-based), a filler material (usually in the form of finely ground silica sand), water, and a small amount of aluminum powder that reacts with the alkaline environment, producing the hydrogen gas that creates the cellular structure of the material. As described in Table 3.2.1, pozzolanic materials such as fly ash and slate waste can be used as a partial replacement for the binder and/or filler material. A typical mix design for AAC is shown in Table 3.3.2 to give an idea of the relative quantities and purposes of the constituent materials used to produce AAC.

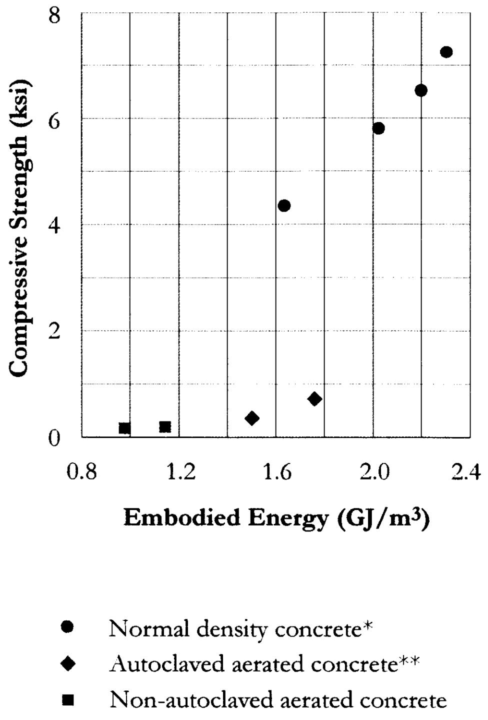
Table 3.2.2
Constituents of autoclaved aerated concrete (source: environmental product declaration according to ISO 14025 for YTONG Autoclaved Aerated Concrete)

Raw Materials	Description	% of Total Dry Mass
Sand	A natural mineral that is majority quartz (SiO2). Ground into a powder, it is a significant raw material for the hydrothermal reaction that takes place during steam-curing.	60–70
Cement	Cement is used as a bonding agent.	15–30
Quick lime	Quick lime is used as a bonding agent.	10–20
Anhydride/plaster	Influences the solidification period of AAC.	2–5
Aluminum	In a powder or stabilized paste form, aluminum is used as the pore-forming agent.	0.05–0.1
Water	The presence of water is the basis for the hydraulic reaction of the bonding agent. Moreover, water is necessary to produce a homogeneous suspension.	50 – 75 % by mass is added in relation to the total mass of the solid substances.

The constituent materials are thoroughly mixed to form a liquid slurry. The slurry is immediately poured into molds where it is allowed to rise. If reinforced members are being produced, reinforcing wires or bars can be placed in the molds before or shortly after pouring the slurry into the mold. During the expansion of the mixture when air pores are generated by the chemical reaction between the aluminum and the slurry, heat is developed by the rising "cake," accelerating the setting of the material and allowing the material to attain sufficient green strength for the cutting and transfer within a few hours after initial mixing. The cast material is typically wire-cut into blocks and panels that are then placed in autoclaves for final curing. The tailings leftover from trimming are recycling directly back into subsequent batches. Autoclaving duration, temperature, and pressure can vary widely, but most commonly the green cakes are subjected to pressures ranging between 4-16 MPa, durations between 8 and 16 hours, and temperatures between 190 and 205°C (380 - 400°F) (Matthys and Barnett 2004, Narayanan and Ramamurthy 2000). Once the material has been removed from the autoclaves, it has reached its nominal strength and is ready for use.

Autoclaving is so prevalent within the industry for two reasons. First, by autoclaving, the curing time is drastically reduced from month timescales to a matter of hours. This has allowed the manufacturing process to be sped up, increasing the quantity of material a plant can produce in a given production cycle. Just as important, autoclaving has been the standard within the industry because a more stable and mechanically superior product can be produced. When the material is autoclaved, "fundamental changes take place in the mineral constitution, which may reduce shrinkage to one-quarter or even one-fifth of that of air-cured product. This is because of the formation of well-crystallized tobermorite in AAC products. The gel form of set cement, as is the case in air-cured products, is converted to a microcrystalline form by autoclaving" (Narayanan and Ramamurthy 2000, 327). This more stable form of tobermorite is the reason for AAC's superior strength and dimensional stability.

Autoclaving has its drawbacks as well. The fact that AAC is cured in high temperature and pressure



*(Sitang and Huiqiang 2005)

**(Environmental Product Declaration for Ytong AAC 2005)

Figure 3.2.1
Compressive strength versus embodied energy plotted for normal density concrete, AAC and NAAC.

autoclaves increases the embodied energy of the material, with about 35 percent of its total embodied energy typically attributed to autoclaving (Environmental Product Declaration for Ytong AAC 2005). When compared to normal weight concrete it has a similar embodied energy profile per unit volume. But considering AAC's reduced strength characteristics, it is easy to see that AAC has an increased embodied energy profile compared to traditional concrete if we are concerned with comparing the two materials once strength has been controlled for. Figure 3.2.1 provides a plot of compressive strength versus embodied energy of two different strength classes of AAC (Environmental Product Declaration for Ytong AAC 2005) as well as embodied energy of various strength grades of normal weight concrete (Sitang and Huiqiang 2005). This starts to give one a schematic understanding of the relationship between embodied energy and strength.

By not autoclaving aerated concrete, the embodied energy profile of the material is reduced, but the resulting material is also weaker and less stable. I have included in the graph in Figure 3.2.1 embodied energy and strength extrapolations for NAAC based on embodied energy data provided by Ytong and strength data from Valore (1954). Efforts to increase the strength and stability of NAAC have included the introduction of fiber reinforcing (Zollo and Hays 1998, Laukaitis et al. 2009). In the US, a non-autoclaved aerated product called FlexCrete™ is produced with fiber reinforcement, which they claim provides resistance to shrinkage and increases its strength.

3.3
Material Properties of AAC and NAAC

Strength in relation to density

There have been a number of models proposed to describe the relationship between the compressive strength of aerated concrete and either the water-cement (w/c) ratio or air-cement ratio, both being directly linked to the relative density of aerated concretes. It is generally accepted that relative density (ρ^* / ρ_s) is the best predictor of the compressive strength of any aerated cementitious material. Autoclaving increases the strength of cellular concrete because high temperatures and pressures during the autoclaving cycle allow a more stable type of tobermorite to form. Tobermorite is one of the types of calcium silicate hydrates that are created during the curing process when cements hydrate. On the other hand, non-autoclaved aerated concrete obtains strength much more slowly, reaching 80% strength only after 6 months. The strength of NAAC is due in part to carbonation in addition to the formation of calcium silicate hydrates, which dominates in AAC (Hanečka et al. 1997). The use of fly ash in both AAC and NAAC has been shown to increase strength to density ratios. Also, compressive strength varies inversely with moisture content (Narayanan and Ramamurthy 2000).

Though there are a number of models proposed for the strength of aerated concrete related to relative density, there is a strong case for the fact that in general, compressive strength increases linearly with solid to pore *volume* ratio (Narayanan and Ramamurthy 2000, 326). In 1980 Watson showed, through regression analysis of a wide range of density AAC made with slate waste, a linear relationship when comparing material properties with what he called *reciprocal porosity* (*Vs*/ *Vp*; the solid to pore volume ratio).

Thermal properties in relation to density

Because aerated concretes have much lower densities than normal weight concrete, they can be considered thermal insulators instead of thermal conductors. Traditional concrete can be used as a "massive material" providing thermal inertia properties that are integral in the design of passive solar buildings. Essentially, massive materials have the ability to absorb and store heat energy, slowing down the transfer of heat through the envelope of a building. This delay effect can be used to great effect when there are periodic changes in temperature on a daily basis. With a low enough density though, aerated concretes can compete with other forms of insulation traditionally used in construction while at the same time providing the thermal inertia benefits typically found in denser materials. This combination of thermal resistance with thermal inertia is arguably the ideal when considering the thermal design of a building's envelope (Ropelewski and Neufeld 1999). By solely focusing on thermally resistant materials in the design of energy-efficient buildings, one is ignoring benefits thermally inertial materials provide. In 1982, the California Energy Commission revised energy standards to recognize the benefits inherent in what they termed "light mass" materials such as AAC (Aroni 1990, 74). In the code, the CEC defined "light mass" materials in general terms: "if the heat capacity of the wall meets or exceeds the result of multiplying the minimum R value by 0.65" (California Energy Commission, 'Energy Conservation Standards for New Residential and New Nonresidential Buildings' [1982]). This consideration of a material's thermal properties beyond just its resistivity means that one is taking into account the dynamic thermal properties of that material. Thermal conductivity is a steady-state measurement of a material's ability to transfer heat energy. To achieve more advanced thermal design of buildings, one needs to take into account the dynamic thermal behavior of the building because buildings occupy a dynamic thermal environment. Standards such as the one first implemented by the CEC in 1982 allow one to meet energy conservation standards through other avenues then just meeting a certain R-value for a wall assembly. By taking into account thermal inertial contributions to the thermal performance of a material, one can calculate an adjusted equivalent R-value for that material. By taking into account this dynamic thermal performance of the material, the CEC code was able to allow for R-values for "light mass" materials that were 21-34% of those required for typical frame construction while maintaining the same energy budget for a building built out of a "light mass" material.

I believe this is a very important concept, in that this material, depending on its relative density, can be both a structural material and an insulating material. Traditional uniform density AAC has always tried to balance the benefits of insulation with the need maintain enough strength so that the material can be viable as a structural material. My goal of trying to create a

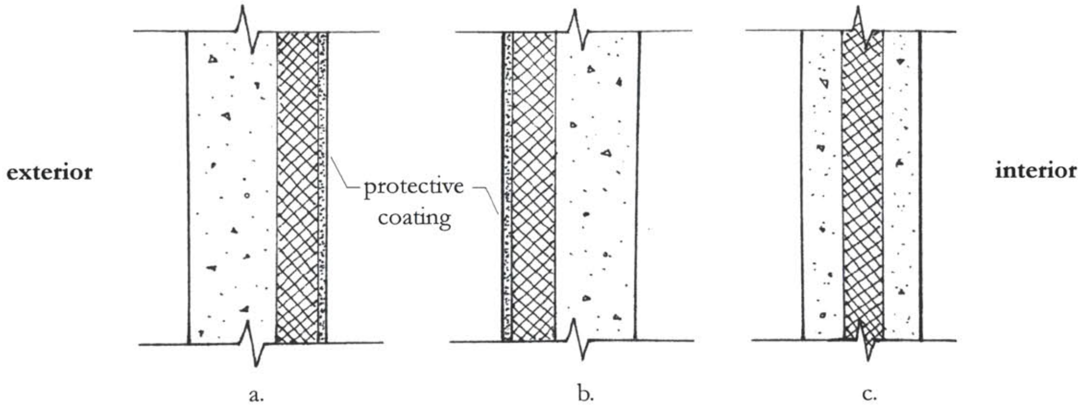


Figure 3.3.1
The placement of mass in relation to insulation is not critical in terms of the thermal inertia properties of the wall, but there are secondary implications: (a) Mass on the exterior: good for fire and weather resistance. (b) Mass on interior: good for night-flush cooling, passive solar heating and radiant heating in general. (c) Mass sandwich: provides benefits found in both (a) and (b). (after Lechner 2000, 457)

variable density material attempts to address this inherent tension between strength and thermal insulating properties by thinking about the material on the macro scale. If we can provide higher density material to satisfy strength requirements in combination with lower density material, we can imagine a superior building material product. The industry has attempted to solve these competing needs in similar ways already. Xella, the largest manufacturer of AAC worldwide, has created essentially a sandwich block. A super lightweight AAC is sandwiched between two panels of normal weight structural AAC.

In general, the thermal conductivity of aerated concrete depends on density and moisture content (Narayanan and Ramamurthy 2000). One of the main issues with aerated concrete is the fact that it is a porous material that readily takes up moisture from the environment. This is an issue because the thermal conductivity of aerated concrete is highly sensitive to increases in moisture content. An increase of 1% by mass of moisture has been shown to increase thermal conductivity by up to 42% (Aroni 1993).

3.4
Current State of the Art in the Industry

In general, there is little work being done to develop methods for casting variable density cellular concrete. Saevarsdottir (2008) has done work to develop vari-

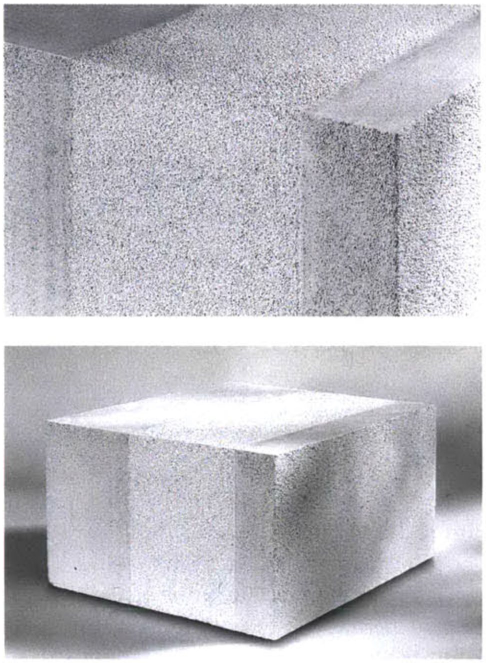


Figure 3.4.1
Xella's Ytong multi layered block with an equivalent lambda value of 0.06 W/(mK) achieved by laminating a layer of highly insulating Multipor between two slabs of normal AAC.
(images from Ytong press release, 2011)

able density concrete panels. He focuses on using aggregates of varying density and only utilizes gravity to produce segregation of aggregates of different specific weights.

It is interesting to note that as far back as 1993 when the RILEM Recommended Practice for AAC: Properties, Testing and Design was published, among the areas for suggested future research that the committee outlined, a need for developing *new elements* with bulk density gradients was mentioned. They suggested "such elements would have greater densities on the outside and much lower density on the inside." They go on to suggest research into developing elements with various combinations of AAC and normal concrete (Aroni 1993, 352).

In the years since, there have been no real developments in this area save for a few isolated examples. The most relevant is a recent product produced by Xella mentioned above, which is a composite of their ultra lightweight "Multipor" mineral insulation sandwiched between two layers of structural AAC. Xella is responding to the demand for highly insulating products in European markets. In 2011 they introduced the product into the Danish market, satisfying the stricter requirements for low-energy buildings in that country. With the introduction of this composite block they have created a product that combines a structural material with one with high thermal resistance. This combination of these two separately available products allows the construction process to be simplified; by laying up one block, both the insulation and structural shell of the building can be installed in one step (Figure 3.4.1).

At a morphological level, this product is addressing the same basic concern I am striving to tackle by creating functional density gradients, but as apposed to their blocks, which are produced by pouring the two types of materials separately, the techniques I have developed are aimed at being able to control this distribution of density within a single poured element. The Ytong block is still essentially just a layering up of different materials (an assembly of materials). The result is a very attractive building component, but does not go as far as what I am pursuing with this research.

At the other end of the strength spectrum, AAC is also being used in combination with high performance concrete to produce composite elements for use in horizontal configurations that experience high bending moments. This reinforcing technology is termed BCE (Block Composed Elements). Unreinforced AAC blocks are pre-stressed and essentially grouted together within reinforced high performance concrete. According to Flansbjer and Hellers (2011), the motivation for this innovation was "to separate the production of building components from the basic production of blocks." This allows high performance long span building components to be produced onsite based on existing block production technology. This technology offers the possibility of creating building components that "surpass the geometrical limits of unstressed AAC panels." Other examples of creating composites of AAC and normal density concrete include the use of AAC as an infill material for the production of composite lightweight panels (Yardim et al. 2011).

These explorations into combining aerated concrete with higher strength concrete are positive developments, but these products still rely on the basic production model where various cast elements are assembled together to achieve a composite. If one could achieve this same outcome within a single casting, the efficiency of production would be greatly improved. This is why I have embarked on a program of study to develop methods for creating variation in density within a single cast element, opening up new possibilities for reinforcing, pre- and post-tensioning.

Chapter 4: Methods

This chapter describes the theoretical context of the research and how the work was approached. The inherent challenges and opportunities that accompany a designer contributing to construction materials research are discussed and a proposal for an investigative framework that could serve to formalize this type of work is outlined. To further frame the work, I discuss precedents for this type of investigation and the benefits that can be derived from designers doing technical research related to building materials. The chapter concludes with an overview of the constraints and goals I have set for myself as I pursued this research. This methodological overview provides the context for the detailed descriptions of the work found in Chapter 5.

4.1
Investigative Framework

Learning by doing

My background is in architecture and design. I studied architecture as an undergraduate and have over three years of experience working in the field. I have always been interested in materials and construction as it relates to design. I can attribute this interest to my early exposure to the building industry, working as a construction laborer and helping to build houses and additions with my father. Before I learned the tenants of good design, I was immersed in the finer points of wood species identification and the relative merits of having a basement as opposed to a crawlspace under your house. I could tell you where your house was lacking insulation (just look for mold problems on the interior of exterior facing walls) and identify dry rot from a mile away.

It was this early appreciation and facility with the "stuff" that made up our built environment that instilled within me a lasting interest in materials and construction. So, when I embarked on an architectural education, it was always colored and informed by my love of the materials and systems that humans employ to create the environments we inhabit. I never really left behind this desire to be involved with materials in an immediate way. After working in an architectural office for a few years I came to the realization that architects more often than not were glorified managers, balancing the wishes of clients with the constraints imposed by budget, code and construction timelines. Sure there were the lucky few who actually got to "do design," but from my vantage point it seemed pretty unlikely I as going to have the opportunity any time soon.

It was at this point that I started to explore other potential pathways forward. I worked on design/build projects in the Himalayas of India, learned from an American master-builder on the art of designing and constructing multistory wooden yurts, and immersed myself in small independent projects such as bathroom remodels and furniture design. All of these pursuits were linked by their hands-on "doing" nature. Eventually I ended up at MIT, working in the building technology program in the department of architecture. The only thing I knew for certain when I started was that I wanted to do work related to materials. I had an idea about what that might entail, but in truth I was just following a vague pull I felt toward *doing*. I was lucky enough to be allowed to embark on a very open-ended and self-directed course of study afforded by the SMArchS degree program.

In looking back on my work for this research project during the last year and a half, I can begin to identify three critical stages. At the time, when I was immersed in these stages, I did not necessarily appreciate the value of each phase, but now with the benefit of hindsight, I will try to argue for the importance of each of these phases of work and propose that working within this type of rubric has unique value.

The first stage I would characterize as the "shock phase." This phase lasted for a few months, and was characterized by a general feeling of disorientation and stasis. It was during this frankly confidence-shaking time that I questioned most my decision to pursue this type of work. Because of my lack of specific knowledge, it was incredibly difficult to know where to begin and how proceed. It was only by doing hands-on work with the material that my sense of stasis began to recede. Once I began working with the material, the feeling of alienation and unease began to diminish, replaced by a physical knowledge and facility that built upon itself and forced me to seek out and learn the relevant technical knowledge of the material. It was only after I had developed a familiarity with the material through this hands-on approach that any direction or focus could be developed.

The second period is what I would call the "learning curve phase." It was during this time that I was able to progress with more confidence and use my growing understanding to propel me forward. Now that I had some basic understanding of how to produce the material, I was able to beef up my analytical knowledge base and narrow in on a topic of inquiry. Through a more directed and informed review of literature, I could now start to establish a stake in the field and identify areas where opportunities for original research were possible.

The final stage, which I'm calling the "free-wheeling experimental phase," was the period of time when I could finally take advantage of my accumulated experience and intuitively pursue a wide-ranging experimental program. I argue that the type of research I have conducted here was only possible through an approach of this sort, and that without going through each of the stages of the process I've just described, my potential for discovery and innovation would have been greatly reduced. It was only through this at times difficult and even seemingly counter-productive process that I could successfully do this kind of work.

This framework I've constructed through reflection on my work in the last year and a half is centered on the idea that creativity coupled with hands-on work are essential for innovation in this type of field. The reason for this emphasis on a hands-on approach is quite simple. I illustrate this by example: some seemingly clichéd yet sound advice given to budding writers is, "just start writing." This maxim implies that the only way to succeed at something is by actually doing that something. It then follows that if one wants to do construction materials research, the most direct way to get into the game is to start working directly with the material of interest. Countless unknowns and fundamental conditions related to the work will only be apparent once one actually tries to create the thing one has imaged (or has yet to imagine). This is the theory underlying the concept of the "prototype." The theory goes: what might look good on paper does not necessarily translate to the real world, and that it is only after prototyping or "mocking up" the real thing that its true viability can be tested.

This prototyping concept comes out of the design and engineering world. It also comes out of the world of the patenting of intellectual property, where the most effective way to claim an invention as one's own is to model or illustrate it. In the early days of patenting in the 18th and 19th century, an actual physical "working model" was required to demonstrate and lay claim to an invention (Pottage 2011). Now it is not common for patent applications to be accompanied by a working model that is delivered to a patent officer, but to this day, detailed diagrammatic illustrations remain a critical component of many patents.

And of course, when looking at this topic through the lens of scientific inquiry, it is not until experiments have been conducted that one can begin to test a hypothesis. All of this gets back to the basic idea that the act of making or doing has value beyond the immediate production of that thing. This brings us to the concept of procedural knowledge and "learning by doing." In cognitive psychology, procedural knowledge is knowledge that is acquired through the performance of a task or action. This type of knowledge is not easily transferred or articulated because much of the knowledge is tacit or embedded within a sensory experience. As opposed to declarative knowledge, procedural knowledge tends to be less general because of the way in which it is acquired is through specific experiences. This can be seen as a downside to this type of knowledge; it might limit one's ability to see the broader context or consider alternatives that go against one's experience, but it is a powerful form of knowledge that deserves recognition in the context of building materials research.

One of the early articulators of the crucial role hands-on learning and procedural knowledge play in education was the philosopher and educational reformer John Dewey. Dewey was an early founder of constructivist learning theory, which held that the acquisition of knowledge came from an active interaction between ideas and experience. His ideas about perception and cognition led to his conclusion that "if knowledge comes from the impressions made upon us by natural objects, it is impossible to procure knowledge without the use of objects which impress the mind" (Dewey 2003). His ideas about learning and society had direct influence on the experimental Black Mountain College in North Carolina, a unique institution founded in 1933 that emphasized interdisciplinary study. The people who were involved during Black Mountain's 24-year history read as a short-list of 20th century's iconoclasts: Buckminster Fuller, Willem de Kooning, John Cage, Walter Gropius, among many others.

It is interesting to note that many of the tenants of constructivist learning, experiential learning, or project-based learning (all related theories of education, but not necessarily synonymous) are adhered to in modern architectural education in the United States. Architectural students are taught to learn through tactile experience. They are told to build a physical model of their design in order to understand it and evaluate its merits. We encourage architecture students to build physical models or draw their designs because the thought is that the actual act of doing will provide insight and expand their understanding and knowledge of the problem they are trying to solve. This idea of learning by doing is deeply embedded in architectural design pedagogy. I argue that this type of activity is critical for the field of construction materials research as well, and that architects and designers are uniquely positioned to contribute to this field because of their training.

Based on this discussion, I propose a model for research and innovation in construction materials that is based on a tripartite investigative process that is semi-technical, semi-design oriented, and semi-intuitive. It goes back to the three stages I went through during the course of my own research: the "shock phase," "learning-curve phase," and the "free-wheeling phase." For one to be able to navigate this uneven process, one has to be able to employ a host of skills and modes of thinking that range from the technical and analytical to the creative and intuitive.

As we know from countless narratives about the creative process and the act of discovery, a new idea or an inspiration can seem to come out of thin air. There is Newton and his apple tree, Archimedes jump-ing out of his bathtub and running down the street yelling "Eureka!" But it has not been until more recently that we've begun to understand the importance of the context from which these eureka moments arise. In Jonah Lehrer's lucid book on the science behind creativity, he begins to bring together some of the most recent brain research on creativity. In it, he begins to "look under the hood" and piece together a much more rich and varied picture of how things are created and discoveries made. First, it is important to recognize the frustration, failures and struggle that tend to come before a particular breakthrough. It is easy to forget all the of bad that preceded the good when recalling a discovery, but as research into the cognitive mechanisms underlying the creative process is starting to show us, "the feeling of frustration–the act of being stumped–is an essential part of the creative process" (Lehrer 2012, 6). In many ways, it is when we give up and stop looking for the answer that it finally comes to us. This is the reason I believe what I'm calling the "shock phase" of the research was an important part of the process. Without allowing for time that might have seemed to be unproductive and pointless at the time, I would have been trying to force something that was impossible at the time.

In addition, I also needed the procedural knowledge gained through hands-on experience before I could even begin to think about generating new work. As I've just outlined, this hand-on work is associated with a designer's sensibility, and was important during this initial stage, but was also essential in the later stages. For example, in the second stage, or the "learning curve" stage, my direct knowledge of the material was valuable because it focused my search for declarative and technical knowledge. Seeking an answer to a question that arose from my experience with the material was much more fruitful than groping around within the literature in hopes of finding something relevant. On the flip side, without the acquisition of technical knowledge outside of the experiential knowledge gained through doing, the hands-on work would have only been able to develop to a certain level. The value of this "learning curve" stage comes from this dynamic pairing of the acquisition of procedural and declarative knowledge.

The final "freewheeling stage" in many ways is the culmination of all of this work. Once one has acquired a certain level of expertise and experience, the ability to creatively develop and generate new ideas is greatly enhanced. It is at this point that intuition and judgment play a valuable role, allowing one to efficiently choose how to proceed by letting experience guide the creative process. In many ways, it is at this stage that all of that time that might have felt wasted in the beginning serves to propel one forward and provides the potential for creation and discovery during this later stage.

Designer as researcher

What does it mean when a designer applies his or her design background and skill set to a research agenda? This is the question I naively bumped into as I began conducting my research. I could grasp the idea of doing design research, conducting research to aid in the design process and collaboration between architects and related disciplines in an effort to pursue a research agenda. This was something that I was familiar with and examples are countless. Instead, what I had stumbled upon was the dicey situation when a trained designer engages in applied research outside and separate from a design practice. I was applying my design training and ways of approaching a problem from a designer's perspective as I attacked the "research" problem, and I did not readily know the implications of this. Very quickly I began asking myself, what does it mean to do research as a designer? What is the result when one conducts research using design skills? What happens when research is informed by design methodologies? I did not have ready answers, only a desire to jump into the problem I had given myself.

I quickly become aware that I had a penchant for editing and being selective about what types of research activities I chose to engage in. I was constantly evaluating possibilities based on their potential to move the work forward. I did not want to do any work that I could not predict any obvious benefit. This natural tendency seemed to align nicely with the goals associated with applied research, mainly that one is not trying to purely generate general knowledge and understanding about the world, but attack a specific problem to be solved.

This starts to address the intuitive aspect of the process that I mentioned in the previous section. Intuition is a way of making connections and constructing knowledge derived from the subconscious. It is closely linked to learning from experience, but deals with experience that one might not be consciously aware of or connections that are not readily apparent that then inform our judgment and perception. According to Carl Jung, intuition is perception via the unconscious (Jung 1976).

The immense success and dominance of Apple is a good example of how intuition can be critical for discovery and invention. Steve Jobs, credited for Apple's wild success, considered himself first and foremost a designer and he seemed to be wholly aware of the importance of the role the unconscious plays when making design decisions. According to Walter Isaacson, Jobs' biographer, upon returning from India early in his adulthood Jobs said, "[t]he main thing I've learned is intuition" (2011). Jobs also talked about his *taste*–his ability to discern–as his most valuable faculty. Transferring this idea of being discerning to a technical, scientific process, we can start to see the benefits when used in applied research. I believe that within this kind of research context, taste and the ability to discern are critical for successful work and that this is the value designers bring to the process. I would argue that successful scientists have this ability, but it seems like the educational system does not emphasize this type of thinking to a great enough degree. This call for a larger emphasis on non-verbal and intuitive thinking as it relates to engineering education is elegantly argued in Ferguson's book titled, Engineering and the Mind's Eye (1994).

Another way to approach this discussion is to think about the motivations and priorities that a practitioner brings to a problem. A designer working in materials research might focus on the aesthetic implications of the work and be motivated by the ramifications for the design of the built environment while an engineer might be enchanted by solving the puzzle of optimizing a material's design. Yet again, a scientist might be enamored with the numbers themselves, wanting to let "pure data" provide direction and insight. I argue that all of these approaches have value when attacking the same problem; it is only when we recognize these differences in motivation and approach that we can begin to understand the diversity in the types of outcomes we see.

4.2
Methodological Precedents

"Never delegate understanding."
– Charles Eames

There is a long history of designers and architects developing new materials and building systems through a design-oriented and creative process that happens outside the traditional modes of production and development of engineering materials. In addition to the architect Johan Axel Eriksson and his invention of AAC in the 1920s, a list might include figures such as Antoni Gaudí, Jean Prouvé, Buckminster Fuller, the Eames', Heinz Isler, and Frei Otto. These figures have propelled building forward through their inventions and designs; they serve as valuable examples for the tripartite investigative process that I outlined in the previous section, blending hands-on learning-by-doing and non-linear creative discovery that stems from training in the design arts with technical understanding and scientific rigor, resulting in an ability to employ intuition and critical discernment when attacking a problem.

I would argue all of these figures had in common this hands-on way of approaching a problem. Buckminster Fuller, most famous for his geodesic domes, is a perfect embodiment of this approach. First and foremost, he generated his revolutionary ideas about society and man's relationship to the planet through *doing*–through prototyping, modeling, and making. His work is interesting for the *way* in which he worked just as much for what he produced. He easily falls into this category of people "doing" in order to solve a problem. He is famously known for creating his domes through graphic methods and physical models as apposed to actually calculating the complex geometry that underpinned the work. Dana Miller's description of his emphasis on artistic and creative practice in her essay in the catalog for the 2008 retrospective exhibition of Fuller's work sums up this way of working nicely:

> *"Fuller's belief in intuition and experientially gained information meant that his design science revolution needed artists as much as scientists and designers. Artists could recognize local patterns and envision ways to translate them into three-dimensional models and universal application. They often did so in advance of legitimizing scientific discoveries. According to Fuller, this was because artists had resisted specialization and maintained their inherent ability to think independently, intuitively, and comprehensively, while rigorous education had forced scientists into institutionalized methodology and specialization."*
>
> *–(Hays and Miller 2008, 23)*

It was easy for critics to couch his work within an atmosphere of pseudoscience, betraying a prejudice that he did not necessarily understand what he was creating. But the power of his ideas and the communicative nature of his work cannot be overestimated. It was precisely *how* he went about his work that inspired so many people to embrace his ideas and designs. Fuller is a figure that is hard to categorize, but I think Michael Hayes's description of Fuller as a philosopher who philosophized through physical modeling is as good as any (Hays 2011).

This way of operating is exemplified by the work of many other luminaries. Frei Otto, the German architect and structural engineer who propelled lightweight structural design and technology forward in the second half of the twentieth century, used highly sophisticated and complex physical modeling and testing to arrive at his elegant and groundbreaking tensile and grid-shell structures such as the Mannheim Multihalle, a wooden grid-shell. As he saw it, the use of physical experiments for design are purely a tool. He stated, "the use of physical experiments in the design field does not itself lead to humane or natural architecture. As with geometrical or computational optimization methods, the experiments only constitute an aid"

(Otto and Gaβ 1990, IL 25).

Heinz Isler was another figure that extensively used physical modeling and experimentation to inform his designs and even dictate them. Before computers were powerful enough to be able to model the behavior of complex, three-dimensionally curved structures, he was constructing highly detailed precise physical models that allowed him to record and understand the internal stresses found in the designs he generated (Chilton 2000).

4.3
Constraints and Goals

Motivations

"We wanted to make the best for the most for the least."
– Charles Eames

My motivations throughout this work have been rooted in a desire to rethink how we might look at construction materials on a conceptual level. Just as importantly, I want to pair this interest with how we conceive the "stuff of building" with a practical hands-on approach that could begin to inform and shape this theory. The intention has been to let the conceptual framework guide the hands-on experimental work, but not stifle any interesting results I might stumble upon during the course of the investigations. I did not want to get stuck on some theory at the detriment of allowing the work itself to guide and constrain the research agenda.

My experimental work is based on a few fundamental assumptions regarding the material I am working with. First, I want to approach cementitious materials in general as being inherently heterogeneous. Second, I want to develop methods by which one can utilize this heterogeneity to produce controlled compositional outcomes. By controlled compositional outcomes, I mean that I want to be able to influence the heterogeneity and be able to decide how that heterogeneity is organized. This concept underlies many techniques and ways of processing natural materials for human consumption and use throughout history (see Chapter 2).

Specifically, within the context of concrete and masonry, there are many examples of these materials being conceived of and deployed as heterogeneous. Probably the earliest and one of the most delightful examples of this comes from the inventors of concrete. Romans are typically credited with inventing concrete, but roman concrete would not have been recognizable as concrete as we conceive of it today. Roman concrete evolved over the centuries from primitive conglomeration of pozzolanic mortar mixed with large chunks of various types of lightweight volcanic rock, stone, and even reused masonry rubble and pottery shards (Lancaster 2005). This highly variable early form of concrete evolved into the highly sophisticated building material used widely by Romans starting in first century A.D. It was only after the disastrous fire that destroyed much of Rome in 64 A.D. and the great building boom that it precipitated, that Roman concrete fully matured as a construction style. This mature form of Roman concrete was at a basic level both "a composite construction material and a style of construction; both were key elements in the Roman architectural revolution" (Lechtman 1986, 101). This construction material was a composite in two senses; first it was a composite of a hydraulic binding mortar and an aggregate, but also it was a composite of brick masonry and concrete. The mature Roman concrete of the first and second century A.D. was a brick-faced concrete, *opus testaceum*. Roman builders laid up single courses of bricks that had pointed backsides that functioned as integral formwork for the concrete that was used to fill the interior of the wall cavity. This resulted in an amazingly robust and versatile construction type that integrated the benefits of masonry bricks with the plasticity and flexibility inherent in concrete construction. The brick face provided durable and pleasing exterior surfaces to any wall, while the interior concrete filled in and provided the mass to complete system.

Purely in order to serve the purposes of analogy, I wish to draw a comparison between this early form of concrete and the type of variable density concrete I have developed over the course of this research project. In both cases, the material is deployed in a

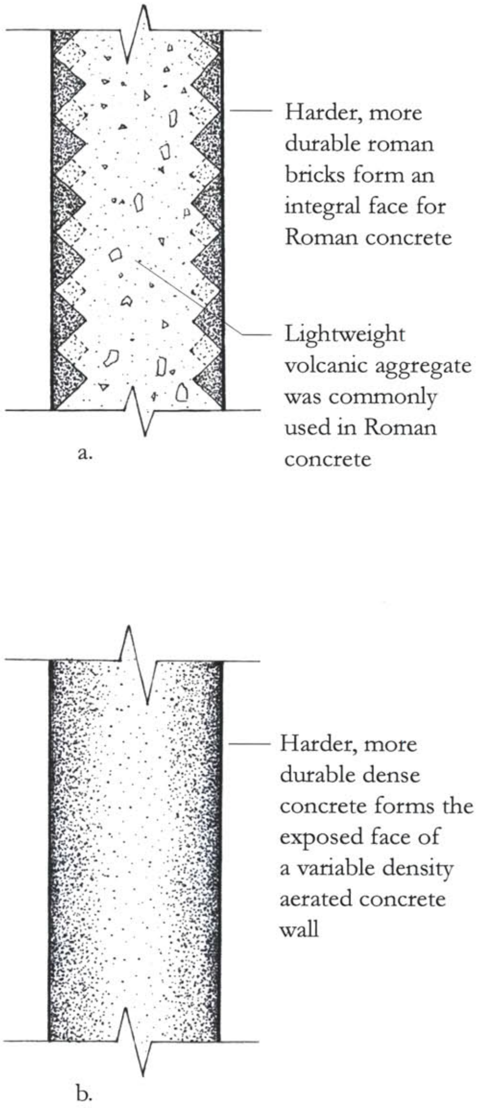


Figure 4.3.1
(a) Plan of brick-faced Roman concrete wall typical of Roman concrete construction after the great fire of 64 A.D. (b) Plan of variable density aerated concrete wall design as proposed in this thesis project.

non-homogeneous manner–the interior of a wall is treated differently than the surface. Figure 4.3.1 depicts a bricked-faced concrete wall typical of second century Roman construction practices. I see this early form of concrete construction as a progenitor and an analog to the variable density concrete I have developed. At a basic level, these two forms of concrete being deployed as a heterogeneous material share more in common than the typical modern form of concrete deployed as a homogeneous material. Much of the infrastructure built out of this brick-faced concrete stands and is still in use to this day. I believe this type of construction is a good model to emulate in the development of better concretes.

Another way that concrete was deployed as a non-homogeneous material by the Romans was at the scale of an entire building. By the time that the Pantheon was constructed in 126 A.D., Roman builders were adept at grading the aggregate *(caementa)* used in Roman concrete. Lower density porous *caementa* is used in the upper portions of the dome of the Pantheon, while denser filler material is used at the haunches of the dome, with the heaviest granite used in the buttresses and foundation. Lancaster has shown through structural analysis of the dome that this sophisticated variation in internal composition of the concrete contributes to its overall stability.

In modern concrete design, there are few examples of heterogeneity being exploited. As I will describe in more detail in the following chapter (Section 5.3 on permeable formwork), practitioners such as Mark West have elegantly shown that the material properties of concrete can be varied at its surface to create a more durable and weather-resistant material. In creating this "case hardening" effect, one is essentially exploiting the heterogeneity of the material by creating a cement-rich region on the surface, different in composition from the rest of the material. Other than this "case hardening" practice though, concrete today is generally not deployed heterogeneously.

4.4
Experimental Methodology

General mix design

Unless otherwise stated within the descriptions of the individual experiments discussed in Chapter 5, the mix design and casting procedure for the experimental work was consistent with the following description. Other than specific instances when I was developing mix designs or testing different mixes, the work was concerned with maintaining a consistent mix design and casting methodology so that the effect that the different casting techniques and casting materials I was experimenting with could be studied independently.

In the fall of 2010, before I had fully defined my research agenda, I began casting aerated concrete to familiarize myself with the process. It was during this time that I developed the mix design that I ended up using for most of the subsequent experimental work. From the beginning, I was interested in using pulverized fuel ash (in my case, Class F fly ash) because I knew that pozzolanic materials such as fly ash have been shown to increase strength-to-density ratios in aerated concretes (Narayanan and Ramamurthy 2000). By using fly ash as a replacement for traditional filler materials such as pulverized silica sand, I would be able to produce a better material both in terms of performance as well as in terms of environmental impact. Because fly ash is a byproduct of energy generation (most commonly, coal-fired power plants), by using this material one is diverting waste from landfills and reducing consumption of the natural resources that the fly ash is replacing. Fly ash can be used as a partial replacement for both filler material and cement binders. When it replaces cement, its positive impact is increased dramatically because one is reducing cement consumption, which is the component of concrete that primarily contributes to concrete's greenhouse gas emissions and energy use profile.

I settled on using aluminum as the chemical foaming agent due to its availability and ease of use. A German producer of technical powders donated aluminum pastes of various grades (see appendix for full list of material and equipment suppliers). Aluminum powder is highly explosive. Because of this, powders that have been stabilized into pastes are commonly used in the production of aerated concrete. The reactivity in concrete of the aluminum depends on the size of the aluminum particles. I used a grade of aluminum paste generally used to produce mid-range densities in aerated concrete, between 500-600 kg/m^3, with the aluminum having a mean particle size of 25-35 µm.

As described in Chapter 3, cement, lime, or a combination of the two can be used as the binder in aerated concretes. I ended up settling on a mix design that was composed primarily of a cement-based binder. The following mix design, shown in Table 4.4.1, was used throughout my experimental work. Some subtle shifting in the ratios occurred over time and is reflected in the percentage ranges shown in Table 4.4.1. This general mix design was used for all of the specimens presented in Chapter 5. The specific quantities and ratios used for each individual experiment are detailed in Appendix C.

Table 4.4.1
Experimental mix design

Constituent Material	% of Total Dry Mass
Class F Fly Ash	60–62
Type I/II Portland Cement	31–32
Quicklime	7–8
Aluminum Paste	0.12–0.16
Water	50 % by mass added in relation to the total mass of the dry constituents

Casting and curing procedure

The dry ingredients are each weighed on an electronic scale with an accuracy of +/- 1 gram and combined in either a bucket or mixing tub depending on the quantity being mixed. The dry ingredients are then thoroughly mixed with a drill-mounted paddle mixer. The aluminum paste is weighed out and combined with the correct quantity of water in a separate container. The aluminum paste achieves a suspension in the water, but the water must be continually stirred to keep the particles of aluminum from settling. The dry ingredients are added to the water and aluminum in small doses and mixed with the paddle mixer. The slurry is typically mixed for 3-5 minutes until it is homogeneous and free of clumps of dry ingredients. After the slurry is fully mixed it is poured into the mold being tested and allowed to rise. As described in detail in the following chapter, the chemical aeration process lasts for about 2 hours. Rising specimens are typically left uncovered until expansion has terminated. At that time, and depending on the type of mold being used, the casting is wrapped or covered in plastic to keep it from drying out. Cast specimens are typically allowed to cure in their molds for a minimum of 48 hours. Once a specimen has been demolded it is stored in plastic and allowed to continue to moist cure for a minimum of 21 days. This curing procedure is especially important for the compression cylinders because proper curing is crucial for the development of strength.

Note: for all of the experiments except for the final beam prototype and the compression cylinder tests, none of the constituent materials were sifted prior to mixing. I had noticed that in many of these specimens that did not contain sifted dry ingredients, there were noticeable conglomerations of unmixed lime particles. As a result, I sifted the lime and Portland cement for the final beam prototype and the specimens I cast for strength and thermal testing. This eliminated any substantial unmixed particles.

Specimen preparation for analysis of internal cellular structure

Because I am interested in the internal composition of the specimens, it is essential to be able to accurately quantify the cellular structure of any casting. To be able to characterize this internal structure, specimens are cut on a band saw equipped with a ¾" carbide-tipped blade. Because of the air-voids in aerated concrete, the material can be dry-cut easily using standard carbide-tipped saw blades. Specimens are typically cut normal to any surface of interest (e.g., normal to a surface in contact with an absorptive molding material). Specimens are typically cut once they have been allowed cure for at least 14 days, but sometimes after much longer periods of time. Once cut, any dust is either vacuumed off or removed with compressed air. It is at this point that the internal structure of air-voids can be qualitatively judged.

To be able to characterize the cellular structure of the specimens quantitatively, I chose to perform a simple image analysis of the cut faces. The image analysis methodology I developed generally follows Nambiar and Ramamurthy's (2007) description on how to characterize the air-void structure of cellular concretes. The exposed cellular structure is carefully sanded with successively finer grit sandpapers (80, 120, 220, 440 grit paper). The resulting polished surface is cleaned with a damp rag and allowed to dry completely. After the specimen has dried, the boundaries of the area to be analyzed are masked off with masking tape and two coats of India ink are applied with a brush to the surface. The ink is allowed to dry for a minimum of 12 hours, and then white talc powder is carefully worked into the exposed voids using a rubber-tipped cell scraper. Once the cells have been completely packed with powder, a final cleaning of the ink-stained surface is performed using a lightly oiled fingertip. Figure 4.4.1 shows the surface preparation process.

This surface preparation effectively creates a binary image, with white indicating a void region and black indicating a solid region. These prepared samples are scanned with an optical scanner at 1200ppi. The uncompressed color image output by the scanner is then thresholded using Adobe Photoshop and processed in ImageJ, an open source image processing software used extensively for image analysis of cellular structures. The detailed workflow used to output the graphs of the solid to void ratios across prepared sectional slices of the specimens shown in Chapter 5 is outlined in Appendix C.

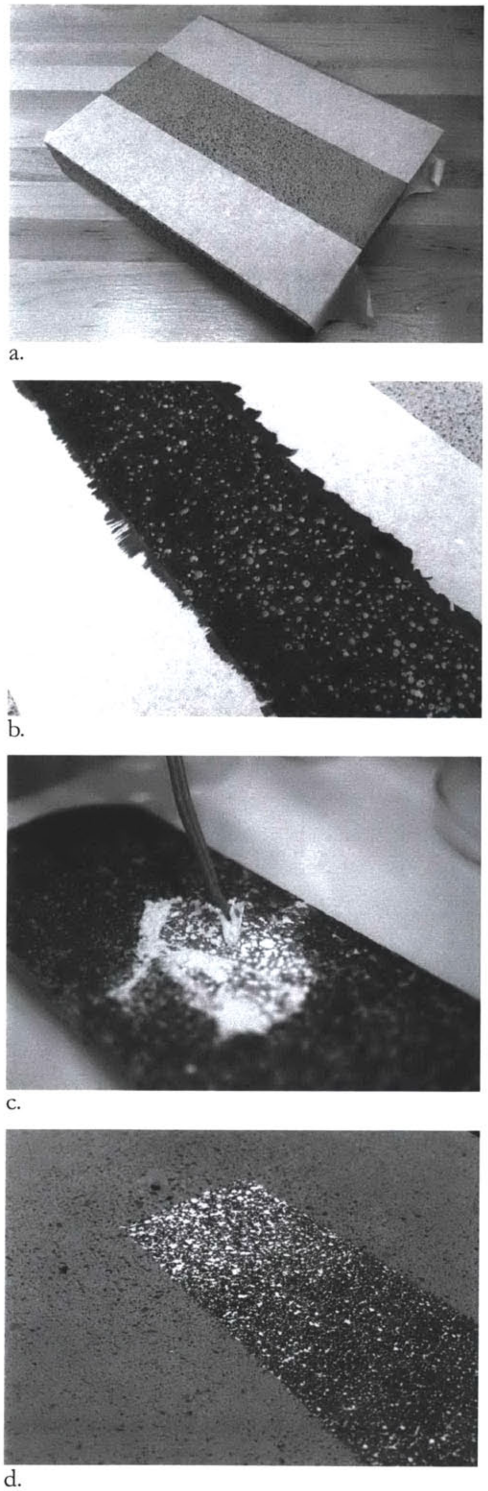

a.
b.
c.
d.

Figure 4.4.1
Specimens being prepared for image analysis. (a) polished surface masked for staining. (b) surface stained with India ink. (c) talc powder being worked into voids. (d) finished region ready for imaging.

Chapter 5: Results

This chapter describes the experimental work I conducted over the last year. A wide-ranging series of experiments were performed. The experimental work resulted in the development of a number of methods for creating density gradients in aerated concrete. These experiments can generally be grouped into two categories: active manipulations and passive manipulations. For each of the individual investigations, the motivations, experimental set up and the results are described. Results are illustrated with cross-sectional images of whole samples and comparisons of densities across sample sections, arrived at through image analysis. At the end of the chapter, results from strength and thermal testing are also given.

5.1
Gravity Tests

Gravity: the enemy of homogeneity

The first set of meaningful results I was able to obtain came from a series of simple tests that looked at the effect of hydrostatic pressure on the chemical air-entrainment process. During these initial forays into producing chemically aerated concrete by hand, what at first seemed to be a problem ended up forming the inspiration for one of the major lines of inquiry within the research. I noticed early on that my castings were not very homogeneous. Despite thorough hand mixing, the blocks produced had an observable bottom, middle and top (Plate 60 and 61, appendix); a certain degree of stratification was occurring that seemed unavoidable.

Stratification is traditionally a concern whenever one is working with cementitious materials. The term usually refers to the segregation in conventional concrete of large aggregate according to the diverse specific weights of the constituents. Bleeding, which refers to the migration of water in fresh concrete, is also a major concern. Segregation and bleeding, which occur due to the effects of gravity, are what one tries to avoid. To paraphrase the general sentiment within the field (Kovler and Roussel 2011, 777), gravity is the enemy of homogeneity. The relative instability of fresh cementitious materials is considered to be a problem to be minimized through the design of the mix: the goal is to produce a mix viscous enough to be stable but not so viscous as to make it unworkable. There is an inherent tension between the need for low viscosity and the danger of segregation caused by the instability of a multiphasic viscous material.

Segregation versus densification

During my initial explorative casting trials (Plate 1, appendix), it quickly became clear that the heterogeneity I was observing was not due to aggregate segregation. One of the key differences between traditional, industrially produced, structural concrete and aerated concrete is the fact that aerated concrete typically lacks large aggregate. What *is* present in aerated concrete is a matrix of air-voids. These air-voids could be said to be, in a certain poetic sense, the negative space left behind by the absence of large aggregate. So, instead of traditional segregation of aggregate found in normal weight concrete, I was, potentially, dealing with a case of air-void segregation. This was exciting because if I could understand the underlying mechanisms causing this segregation, I could theoretically exploit them to produce controlled gradients within the material. Another possible explanation for stratification within the cast was that the build-up of hydrostatic pressure at the lower bounds of a freshly cast element might inhibit formation of air-voids or even cause them to collapse.

The idea that gravity can influence the composition of homogeneous, cementitious materials interests me because of the potential opportunities it can provide. As I've outlined above, concrete is traditionally treated as a homogeneous material composed of a number of constituents that interact in complex ways. The material is constantly being designed and manipulated in an effort to maintain a uniformity throughout. But try as we might, there will always be some degree of segregation and heterogeneity introduced into any concrete casting as a result of the gravitational forces acting upon the mixture. I am interested in reimagining how we think about this material, and instead of fighting this tendency for stratification, letting the material do what it wants to do. One of the fundamental theoretical underpinnings of my work with cementitious materials is to exploit these effects and embrace the material as something that is heterogeneous.

Columnar tests

To investigate these gravity-induced mechanisms and understand what might be happening to the matrix of air-voids at different locations within a cast element, I cast a series of simple prismatic samples in rigid molds (Plate 2, appendix). Because I was interested in the vertical stratification that occurs due to the effects of gravity, I wanted to design an extreme configuration so that any segregation would be accentuated and more easily studied. Thus I decided to cast in a vertical or columnar configuration, pushing the limit of the casting geometry in a vertically oriented linear condition in order to produce more dramatic stratification.

Initially, I cast two columns, both of the same proportion but one twice the size of the other. The molds used for these two tests had inside dimensions of 2 in. x 2 in. x 12 in. and 4 in. x 4 in. x 24 in. My reason for casting at two scales was to be able to study stratification in relation to any size effects that might present themselves. This was important because I wanted to understand what role scale might play when dealing with stratification. My main concern was whether the size of a cast element in relation to the scale of the cellular matrix would have any effect on stratification.

These two tests produced dramatic enough results that the variation in the cellular structure was apparent upon visual inspection of the internal cellular structure (Plate 3 and 4, appendix). The internal structures of these two samples are shown in Figures 5.1.1 and 5.1.2. These two initial samples display a relatively uniform matrix of air-voids throughout the top three quarters of the column. In the bottom quarter of the column, however, the cellular matrix changes, smoothly transitioning from a matrix composed of larger voids to one composed of smaller and smaller voids, with the highest solid-to-void ratio occurring at the bottom surface of the column. When comparing these two

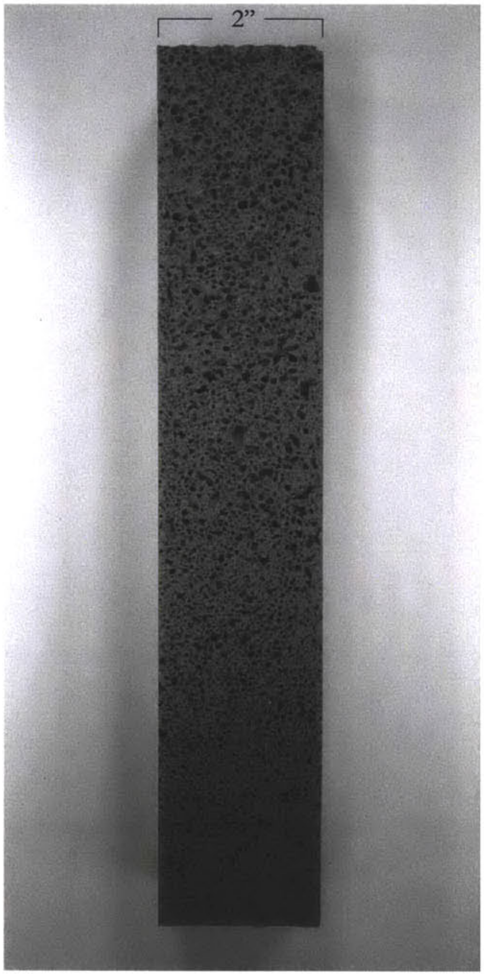
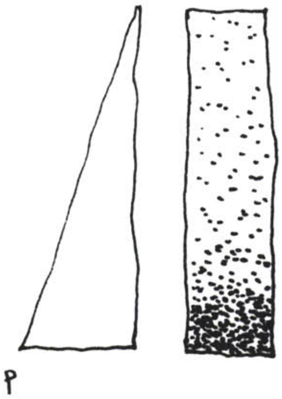


Figure 5.1.1
2 in. x 2 in. x 12 in. column with internal cellular structure exposed



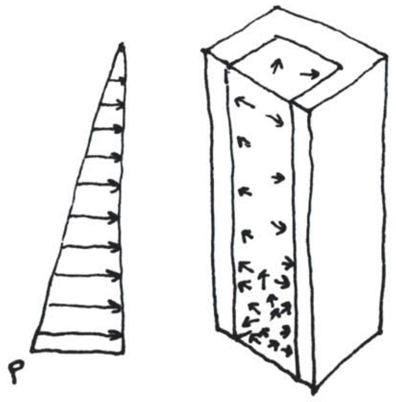


Figure 5.1.3
Hydrostatic pressure – vertical pressure variation due to the force of gravity

tests, it is clear that at these two scales, stratification generally occurs independent of any size effect. This does not rule out size effects that might occur at substantially larger or smaller scales, but confirmed for me that within this general range, the phenomenon I was dealing with was fairly reproducible independent of the size of the object.

One of the first questions that needed to be asked based on these experiments was whether the migration of air bubbles within the fresh matrix is causing the stratification, much like the stratification of large aggregate that can occur in normal density concrete, or if there was some other explanation for the variation in the cellular structure. Because the variation in cellular structure is not due to a change in the quantity of voids at different locations, but due to a change in the relative size of the voids, the most likely reason for the stratification was the build-up of hydrostatic pressure at the base of these samples. Based on these columnar tests, I concluded that the variation in hydrostatic pressure is likely the dominant reason for densification at the base of the column samples.

Hydrostatic pressure refers to the pressure exerted by a fluid due to the force of gravity and can be calculated for liquids using the simple formula $p = \rho g h$, where p is the hydrostatic pressure (Pa), ρ is the fluid density (kg/m^3), g is gravitational acceleration (m/s^2), and h is the height of the liquid column above the test volume being measured. This means that pressure increases proportional to the increased height of the fluid above a particular test volume (Figure 5.1.3).

Based on this assumption, then, in actuality the pressure build-up in the larger cast should have been greater than in the smaller one, resulting in greater den-

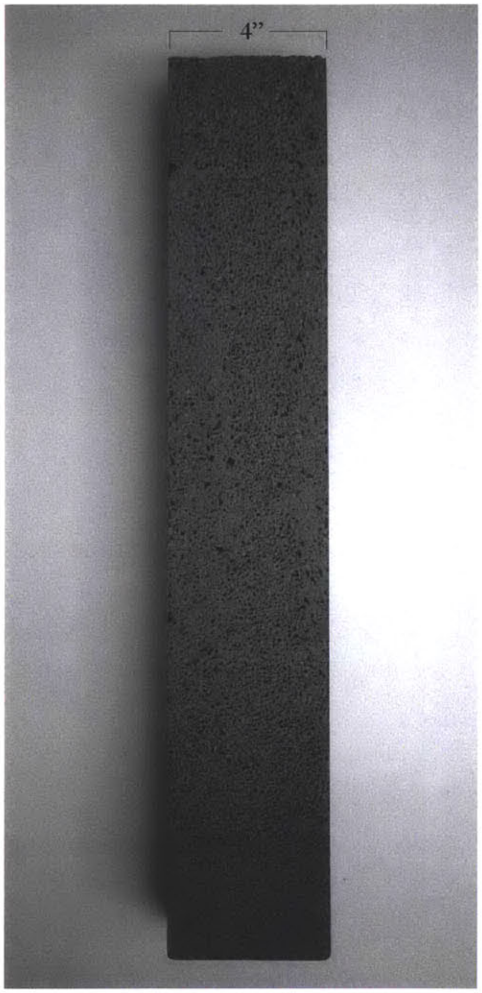


Figure 5.1.2
4 in. x 4 in. x 24 in. column with internal cellular structure exposed

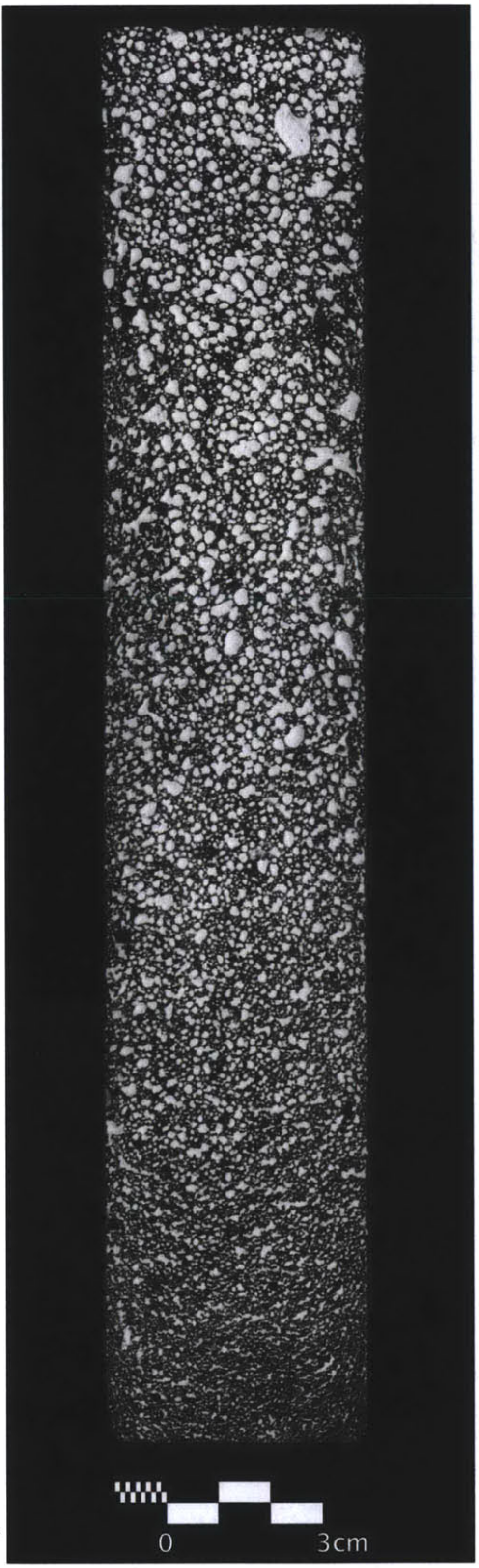


Figure 5.1.4
2 in. x 2 in. x 12 in. column displaying internal cellular structure prepared for image analysis.

sification. To interrogate at this relationship, I decided to cast another set of columns, this time with the same plan dimension as the smaller column (2 in. x 2 in.), but this time 24 in. tall. I figured that if I doubled the height, I would be able to see an increase in the densification if it was indeed hydrostatic pressure that was causing the change in the cellular structure.

By comparing the solid to pore volume ratios at the bottom of the two columnar samples shown in Figure 5.1.5 and 5.1.7, one can see that a ratio of about 0.7 is achieved in the 12 in. column, while a solid to pore ratio of almost 0.95 is achieved in the 24 in. column. This confirms that higher hydrostatic pressures result in higher densities.

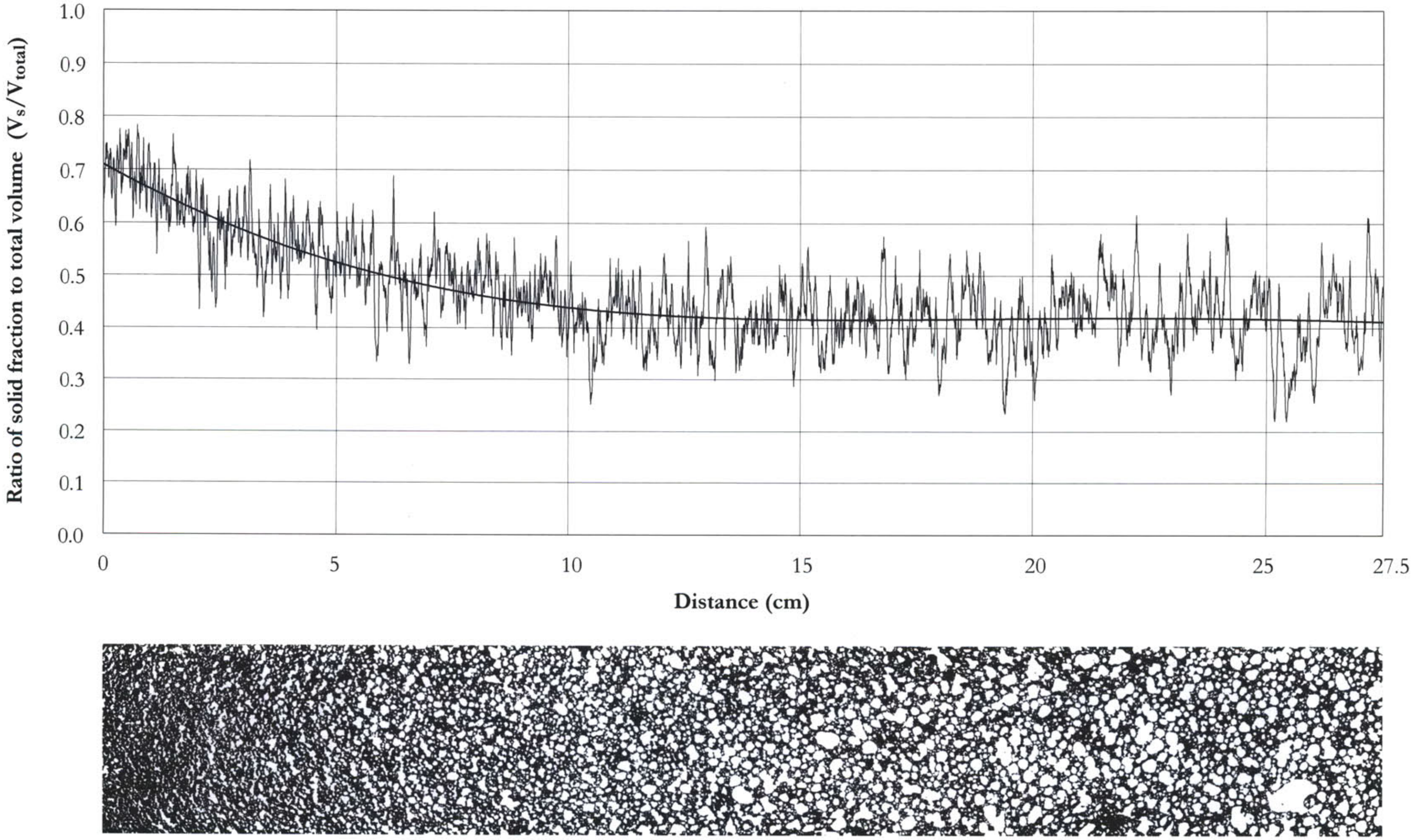


Figure 5.1.5
Image analysis of 2 in. x 2 in. x 12 in. column showing air-void distribution

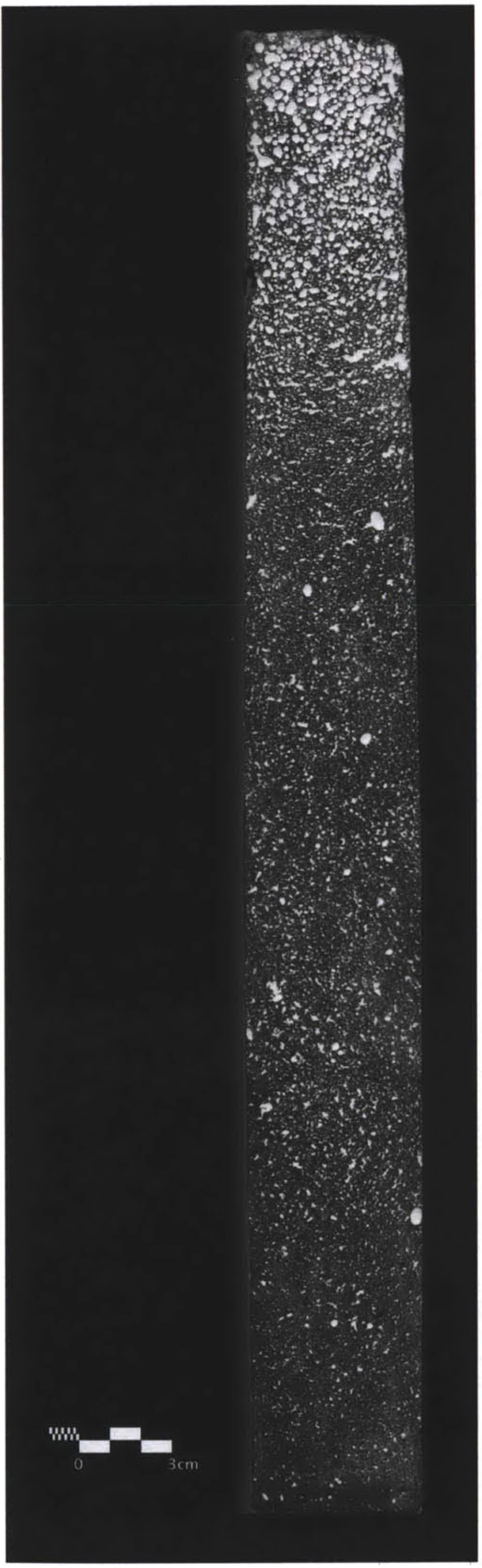


Figure 5.1.6
2 in. x 2 in. x 24 in. column displaying internal cellular structure prepared for image analysis.

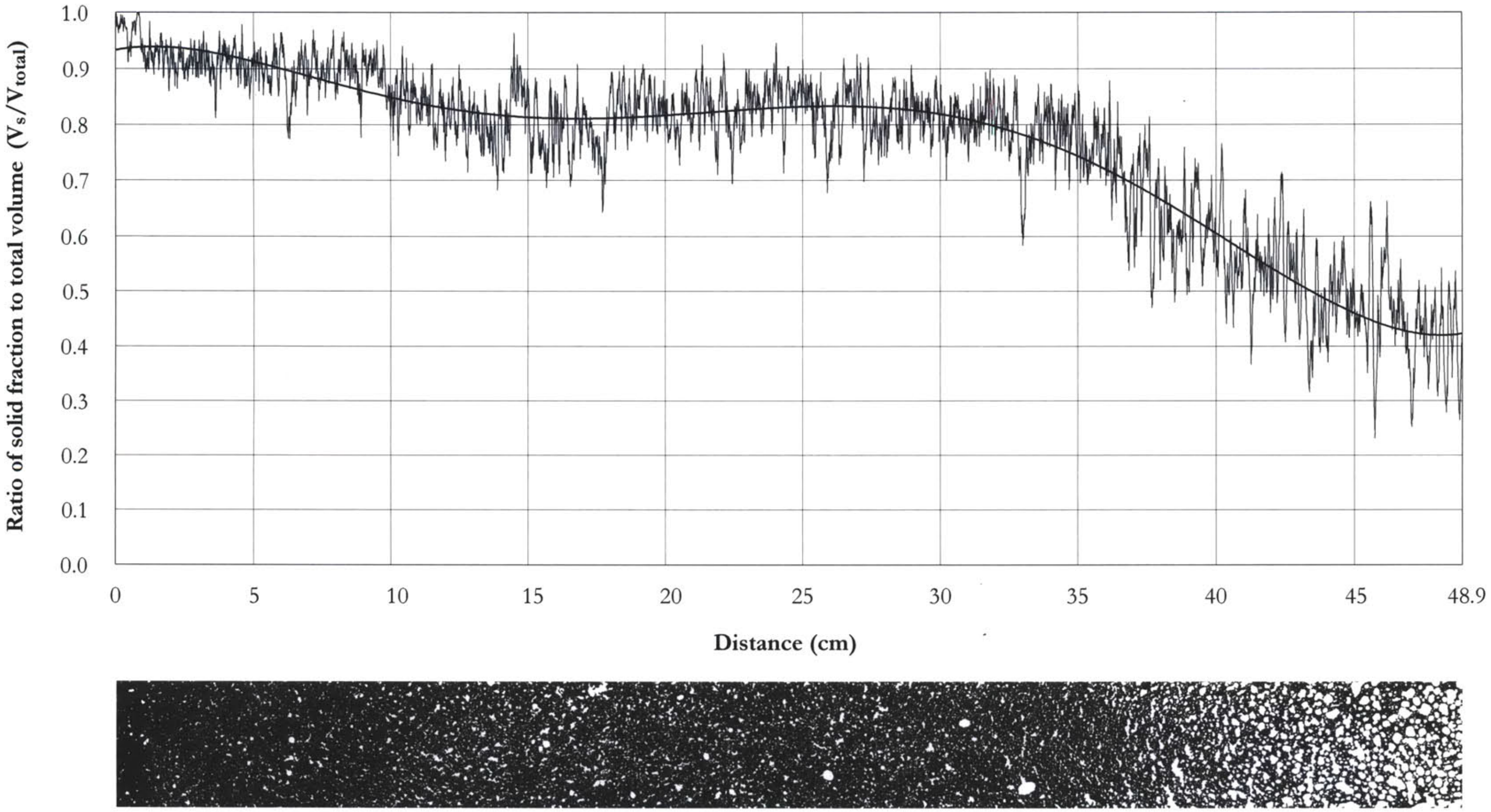


Figure 5.1.7
Image analysis of 2 in. x 2 in. x 24 in. column showing air-void distribution

5.2
Rotational Forming Tests

Exploiting centrifugal action to achieve radial gradients

This series of experiments was designed to test the effect of centrifugal action on the fresh air-void matrix as it formed. This work was a direct outgrowth of my initial study of the effects of hydrostatic pressure that results from gravitational force. I hypothesized that if a gradient of density could be achieved through the build-up of hydrostatic pressure within a cast, then the application of centripetal forces should be able to produce similar results.

These tests are in the same vein as the gravity tests in that they were designed to be able to study what happens when a force is applied to the material as it is being formed. By spinning the material, I am essentially recreating–but in a different configuration–what occurs when gravity acts upon a static fluid. The key difference between the force of gravity and the radial forces that act on a spun liquid is the fact that gravity can be seen as a passive mechanism for affecting the material, while centrifugal action can be seen as an active mechanism.

Despite the limitations and potential drawbacks of employing this active mechanism, I was interested in performing these tests because utilizing gravity only gives limited options in terms of the configuration and orientation of the gradients. By spinning a cast element, one can create new geometries, mainly radial gradients.

Before embarking on these rotational tests, I ran an experiment to observe the aeration process in greater detail. Up until this point, based on my own observations and descriptions found in the literature, I knew that aeration took place during the first few hours, after mixing the constituents and before the fresh concrete attained its "green cake" rigidity. I wanted to accurately record the aeration process to pinpoint the transformations more precisely. This experiment allowed me to establish a baseline for the rate of aeration for a typical casting and to define precisely the window within which aeration occurred. This served two purposes. First, by establishing the timeframe within which aeration took place, I could determine the window within which I needed to work to affect the aeration process. Second, by observing the rate of aeration, I could determine if there were periods of higher activity that might present opportunities for the greatest influence on aeration. I already knew, based on casual observation, that the rate of expansion was not constant throughout the foaming process; the test confirmed this and gave a detailed characterization of the expansion profile.

The specimen used for the observation of aeration was cast in a 5 mm x 5 mm x 12.5 mm rigid foam mold. One side of the mold was replaced with a ¾ in. thick lucite plate to allow observation of the aeration process. A scale was placed behind the lucite face to measure the expansion of the slurry (Figure 5.2.1). A digital camera was set up on a tripod and a picture was taken every 30 seconds for two hours while the mixture rose.

After combining the wet and dry ingredients and mixing them for approximately 3.5 minutes, the slurry was poured into the mold so that it formed an initial 5 cm cube. No observable expansion began occurring until 10 minutes after initial mixing. In the first 5 minutes of rising, the slurry expanded at a rate of 0.2 mm/min. From 15 to 20 minutes after mixing, it rose at a rate of 0.5 mm/min. From 20 to 50 minutes it rose at a roughly constant rate of 0.7 mm/min. After 50 minutes, the aeration process continued, but aggregate expansion did not occur at the typical 0.7 mm pace. The coalescence of air-voids and their collapse was observed at this point. Between 50 minutes and 1:10 after initial mixing, the rate was roughly 0.3 mm/min. A measureable rate of expansion was not observed after this time, though periodic rise and fall at the surface was visible for an additional 30 minutes due to air-void coalescence and collapse. After two hours, there was no visible sign of activity and the matrix seemed to reach a stable condition. In brief, expansion ceased after about one hour, with any residual activity due to extant chemical reactions ending after two hours (Figure 5.2.2).

Based on this experiment, I concluded that I had a window of roughly two hours where any manip-

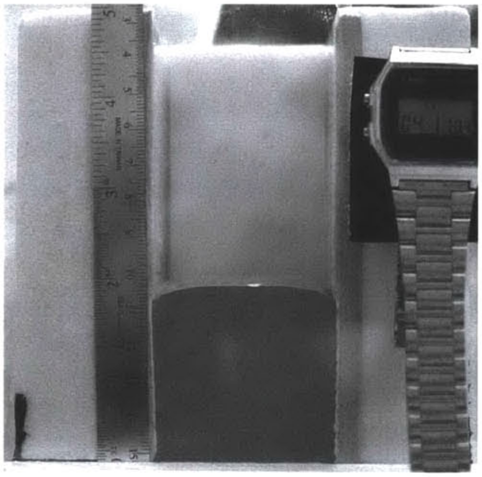


Figure 5.2.1
Foaming analysis specimen setup

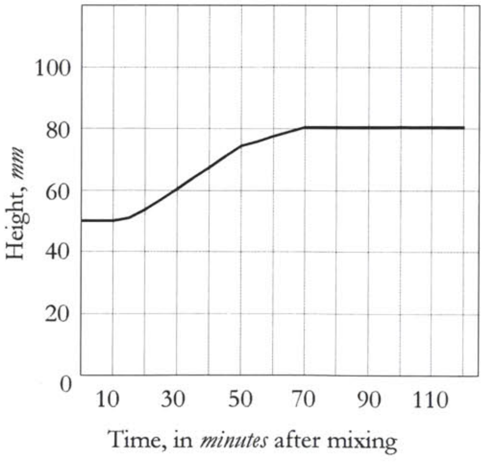
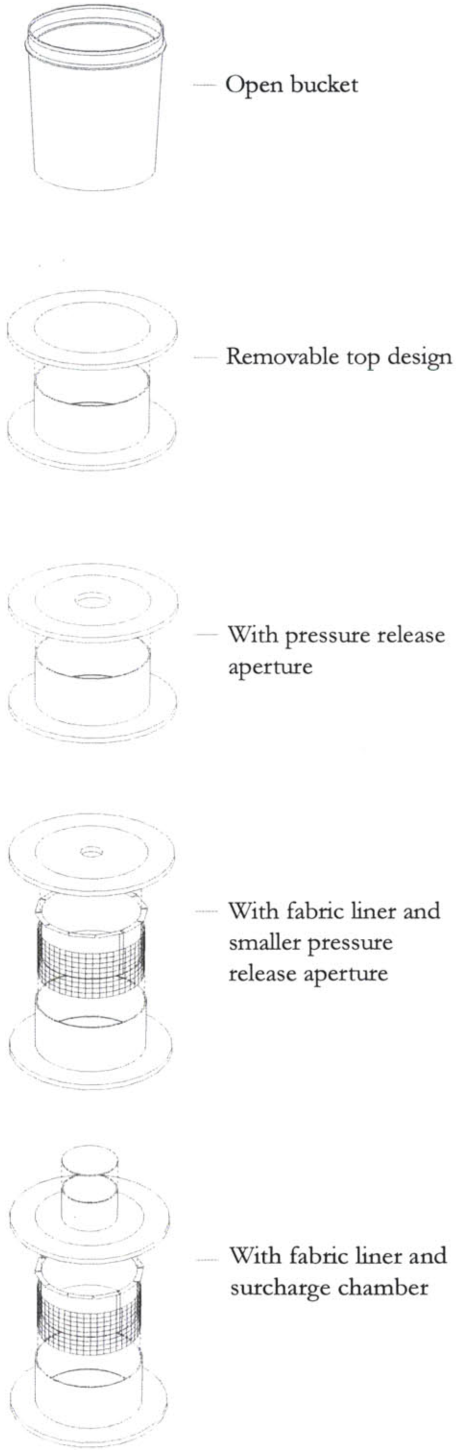


Figure 5.2.2
Expansion of chemically aerated slurry over time

Figure 5.2.3
Evolution of centrifugal mold design



ulations to the material–efforts to affect the foaming process–needed to take place. This information helped me to design the subsequent rotational experiments. I now knew that if I wanted to retard the formation of air-voids through the application of centripetal force, then I should focus my efforts during the 40-minute window of time that starts 20 minutes after mixing and ends about an hour after mixing. Because the air-void matrix is fragile during and immediately after the aeration process and will experience successive collapse if disturbed, I knew that any applied forces (in this case, the forces that result from spinning) needed to be constantly applied to minimize any unpredictable collapse or damage to the matrix. Because of this concern, I decided to err on the side of caution and spin the specimens at a constant rate for a much larger window of time to rule out any unpredictable collapse during the spinning cycle or during the ramping up and down at the beginning and end of the cycle.

I cast five cylinders over the course of my experimentation with centrifugal molding. All of the cylinders were cast on a pottery wheel that had been retrofitted to accept custom-made cylindrical molds (Figure 5.2.3). These molds were designed to be easily mounted and sealed once they had been filled with the fresh mix. The design of the molds evolved as I refined the process. The first mold was made from plywood and plastic and consisted of a simple 10" diameter cylinder with a removable lid (Plate 5-7, appendix). The second specimen was cast in a plastic bucket without a lid so that I could observe the mixture as it was spun. These first two tests were conducted on the same day. Because of concern that the molds would leak or become unstable during the spin cycle, these first two casts were spun at about 60 cycles per second. As can be seen by looking at the cross-sectional profiles of these two specimens (Plate 12 and 13, appendix), the centrifugal force acting on them was only large enough to begin to create a sort of meniscus on the upper surface of the concrete. It is also clear that spinning at these speeds had no measurable effect on the internal cellular structure. Based on these first two attempts, it was obvious that I needed to increase the spin velocity dramatically if I wanted to generate enough force to have any affect on the cellular structure. This turned out to be quite a challenge for a number of reasons. Because the slurry expands and produces hydrogen gas during the aeration process, I had to take into account this expansion and the associated build-up of pressure inside the mold. Also, because I was planning on spinning at higher speeds, the overall sturdiness of the mold needed to be increased while still allowing easy setup and demolding.

For the third cylindrical test, I rebuilt the mold so that it could be completely sealed save for a small aperture centered on the top of the lid to relieve any pressure build-up during the expansion of the slurry. To account for the slurry's volume increase during the spinning cycle, I did not completely fill the mold, only pouring in roughly two-thirds of the overall volume with the expectation that the slurry would expand to about 150% of its original size. This third test was spun at about 120 rpms–twice the speed of the first two tests–but it is clear from looking at the internal cellular structure (Plate 14, appendix) that this increased speed had little effect on the formation of air-voids. Equally disappointing was the fact that the mixture did not completely fill the mold. Because of the higher spinning velocities, the material distributed completely to the sidewalls of the mold, leaving a void in the center and creating a sort of donut-shaped casting. I had underestimated the amount of expansion and now knew that I had to be much more careful about providing the appropriate amount of fresh material. I did not want to over-fill the mold, causing leakage and potentially catastrophic failure during spinning, but I also did not want to under-fill it.

To solve this problem, I added an expansion chamber on the top of the cylinder. This auxiliary chamber allowed me to completely fill the main chamber of the mold without fear of pressure building up as the mix expanded. As the mix aerated during the spin cycle, it could fill the expansion chamber instead of being confined to the main chamber and building up pressure. I could now spin the cylinder at higher speeds and produce a solid specimen without having to worry about catastrophic failure during the spinning cycle, while at the same time providing enough fresh mix to completely fill the entire mold. Because I was using a pottery wheel for these tests, which had a maximum rotational velocity of around 200 rpms, I was limited in my ability to test at higher speeds. I was interested in staying within these lower rpm ranges because I expected that dramatically higher rates would have much less practical applicability within existing precast production models. Though spun-cast hollow concrete poles and columns can be spun at rotational speeds of up to 1000 rpm (Kaufmann and Hesselbarth 2007, p. 716, Taranu et al. 2009), I was instead interested in applying alternative techniques in order to achieve densification. At the end of the next section dealing with fabric forming experimentation, I detail the final experiment I conducted using a centrifuge mold. In this final spinning test, I incorporated fabric-forming techniques with the centrifuge formwork experiments. Before describing this hybrid method and the results I was able achieve with it, I will first present the fabric-forming experiments that informed the final centrifugal casting experiment.

5.3

Fabric Formwork Tests

Active formwork

My fundamental objective throughout this hands-on experimental work was the development of casting techniques that allow one to effectively vary the mix composition within a single cast piece of material without having to pour individual layers of material. Instead of trying to achieve gradations of material properties by layering up the material (one of the common ways composite materials are produced), my central motivation was to try to influence the homogeneous material as it is being formed, and as a consequence, generate internal variations in material properties depending on where the influence is being exerted (Figure 5.3.1).

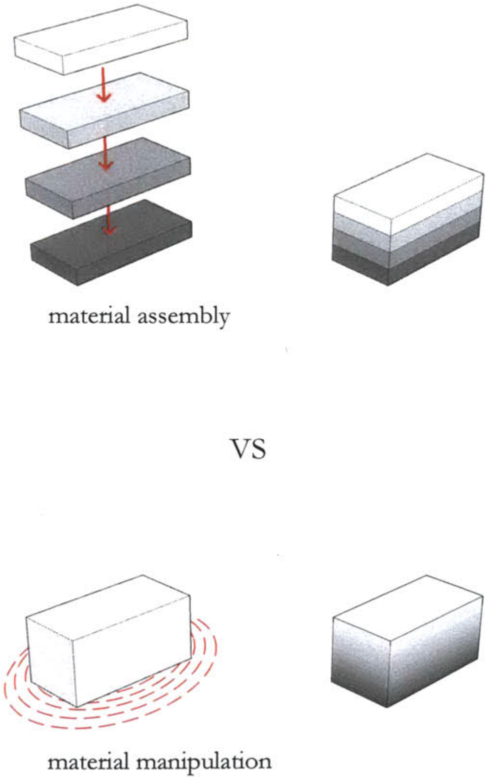


Figure 5.3.1
Assembly of material versus manipulation of material to achieve a desired internal composition

For this work, the material property of interest is density. Chemically air-entrained concrete is uniquely positioned to be manipulated in this way because of the distinctive way in which it is produced. As I have described, there is a window of time during which the material undergoes a dramatic transformation both chemically and morphologically. It transforms from one fundamental material type to another, from a liquid to a cellular solid. If one can locally affect the material as it undergoes these transformations, then one can create variations in material properties within a single cast element. This was the basic assumption that underpinned the work.

The utilization of formwork has been the primary method by which I have tried to locally affect the material as it aerates. By exploiting the molding material as a medium that interacts with the mix during this transformation process from liquid to cellular solid, I am employing the mold as an actor that *actively* influences the internal composition of a resultant cast element.

Beyond formwork as a dictator of geometry

One of the concepts central to my research is the notion that formwork has the potential to do more than solely determine the geometry of a cast element. The word "formwork" implies something that is physically forming something else. On the other hand, the term "molding" suggests a manipulation acting upon that which is being molded but does not necessarily suggest form-making. For example, to "mold something" could mean to influence its development. The interesting thing is that when we use these two words–formwork and mold–literally, we usually mean something that shapes an amorphous material into a specific geometry. I contend that the formal aspects should be signaled by the language one uses. I am interested in pulling apart the language so that one can delineate the different elements of a mold. For example, there might be a structural formwork that dictates the geometry of a cast element and a molding element that influences the development of the cast material as it's being formed.

As I have described in Chapter 2, what interests me is this *interaction* between the mold and that which it is molding. One of my first hands-on explorations in this area was the use of permeable formwork. It has been shown that permeable casting materials can pro-

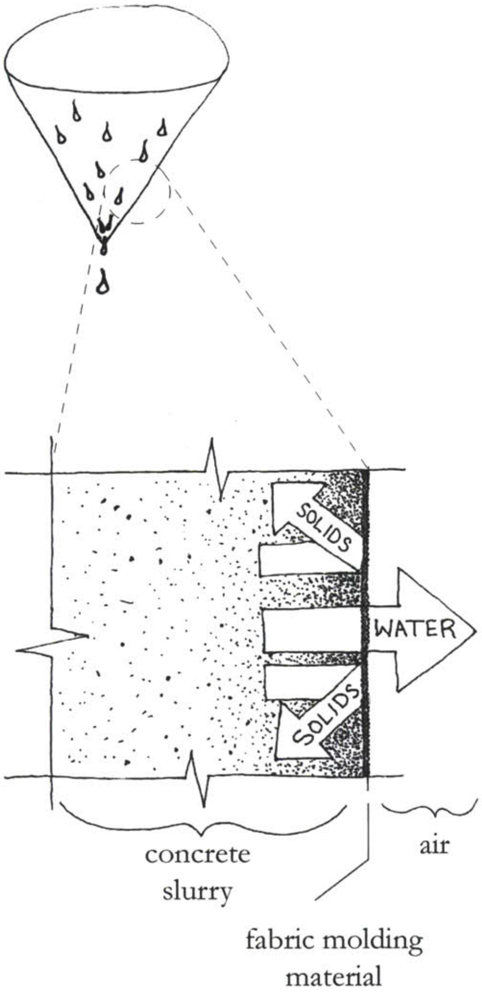


Figure 5.3.2
Permeable formwork

duce improvements in strength and durability on the surfaces of traditional concrete (Schubel et al. 2008, Coutinho 2001, Al Awwadi Ghaib & Górski 2001, Malone 1999, Nolan et al. 1995). This is due to the loss of excess mix water through the fabric formwork, which improves compaction of the matrix and reduces the water-to-cement ratio. My interest in casting chemically aerated concrete in permeable formwork was spurred by the potential influence this water-reducing mechanism could have on the formation of the cellular air-void matrix. By casting in permeable fabric, I was dealing with a molding material that had the potential to do more than just create form (Figure 5.3.2).

Mix design and water content

The water-to-cement (w/c) ratio of any cementitious material is a critical determinant of the strength and durability of the final cured product. When the water content increases in relation to the amount of cement, one sees a decrease in strength (Nilson et al. 2004, 31). This is due to the voids created by the excess free water leftover after hydration. Typically, the water-cement ratio is determined by the rheological requirements of the mix; essentially, enough water must be added to give the mixture sufficient workability so that it will fill a formwork completely. This is because the quantity of water required for proper hydration of cement is less than the amount typically needed to make the mixture workable. One of the ways this issue has been addressed in the industry is through the use of organic and inorganic plasticizers and super plasticizers. By "reducing the interparticle forces that exist between cement grains in the fresh paste," plasticizers provide the workability needed in typical concrete mix design while allowing one to maintain lower w/c ratios within the mix, maximizing strength and durability (Nilson et al. 2004, 37).

The use of permeable fabric formwork can also start to address some of these issues. In their paper looking at the mechanical properties of concrete cast in fabric formwork, Al Awwadi Ghaib & Górski assert, "fabric formworks could be a solution to the problem of combining a sufficiently high workability with the minimum w/c ratios." If, through the use of permeable formwork, one can reduce the w/c ratio *after* conveying, placing and compacting, then the inherent tension between workability and the minimization of w/c ratios is conveniently sidestepped.

Predicted effects of permeable casting materials on the formation of cellular structures in chemically aerated concrete

For my experimentation, I hypothesized that in addition to increasing the strength and durability of the material, reducing the water-to-cement ratio of aerated concrete through the use of permeable formworks could effect the chemical aeration. I postulated that if the mixture had a low enough water content, the voids generated by the production of hydrogen might either collapse or not even be able to form because of the stiffness of the mix. Based on the established research looking at the use of permeable formwork in conjunction with traditional concrete, it is clear that the migration of water through the membrane forces air bubbles out of the mix, compacting it and making it more cement-rich. I hypothesized this could also be a significant mechanism for causing densification in aerated concrete. When I set out to study the use of permeable molding materials in conjunction with aerated concrete, I was hoping to combine a densification effect with the increase in strength and durability that has already been shown in the research on traditional, normal-weight concrete. By applying this unique forming method to aerated concrete, the potential for producing dramatic results was exciting.

Conical fabric tests

To look at the effects of fabric forming on the aeration process, I cast a series of conical specimens using different fabrics (Images 15-22, appendix). I cast in an inverted cone shape for two reasons. First, I wanted to be able to cast in a configuration where the build-up of hydrostatic pressure was exaggerated. By casting in a cone with the tip oriented down, the hydrostatic pressure would vary from zero at the top surface to the maximum at the tip. The second reason was that casting in a hanging conical configuration proved to be one of the simplest ways to cast specimens in fabric; only one seam is required, and the form becomes rigid with minimal distortion when filled with a viscous liquid. An unintended benefit of casting in this configuration was the ease with which I could collect and measure the quantity of water that drained from the mold. The free water collects into droplets that then roll to the tip of the cone for easy collection (Figure 5.3.2).

To be clear, these fabric tests looked at permeable formwork when used in an environment where hydrostatic pressure is present. This means that technically, these tests looked at the effect of hydrostatic pressure when combined with permeable molding materials. By combining the two, one can effectively create an environment where water is actively driven out of the mixture near the surfaces of the cast element. Before doing these tests, I did not know under what conditions (level of permeability of molding material or amount of hydrostatic pressure) one would see substantial levels of water seepage. Instead of trying to calculate the fluid dynamics of the interaction between the mold and slurry, I cast a series of conical pieces using different fabrics and observed the levels of drainage I was able to achieve. I tested three different fabrics. The first was an impermeable synthetic fabric. This fabric was used as the baseline to measure the levels of densification achieved by the permeable fabric above and beyond densification one would see solely as a result of hydrostatic pressure. The second was a gas-permeable synthetic fabric that did not exhibit high levels of liquid permeability based on simple testing in water. The third fabric was a finely woven, thin cotton chintz that exhibited high levels of liquid permeability.

These three fabrics were used to make hanging molds that could be reused. See Figure 5.3.3 showing the fabric molding setup. After mixing and pouring the slurry into the molds, I manipulated the fabric by hand to work out any large air bubbles and compact the mixture before substantial aeration began. The impermeable fabric exhibited no signs of moisture penetration. The low-permeability synthetic fabric exhibited some wetting at the vertical seam and at the tip of the cone, but only an occasional drop of water formed at the tip, with no substantial quantity of water escaping the mold. The cotton chintz fabric exhibited complete saturation, with drops of water forming on the surface of the mold and traveling down to the tip of the cone. 375 mL of water was collected in the first three hours after pouring, which equaled 19 percent of the total 2 liters of water used in the mix. All of the fabric castings were wrapped in plastic to keep the surface of the fabric moist, thus ensuring proper hydration of the cement even with the removal of these substantial quantities of water.

As can be seen by visual inspection of a sectional cut through the cones (Figure 5.3.4, 5.3.6, 5.3.8), the use of permeable fabric saw the production of higher density material along the outside surface of the cones, with the most dramatic densification occurring at the tip. Image analysis was performed on three of the samples to compare the vertical density gradients found in the conical sections (Figure 5.3.5, 5.3.7, 5.3.9).

These tests with permeable molding materials has shown that in addition to improvements in surface quality that can be achieved when used to form conventional concrete, fabric forming can be used to regulate the density of cellular concrete.

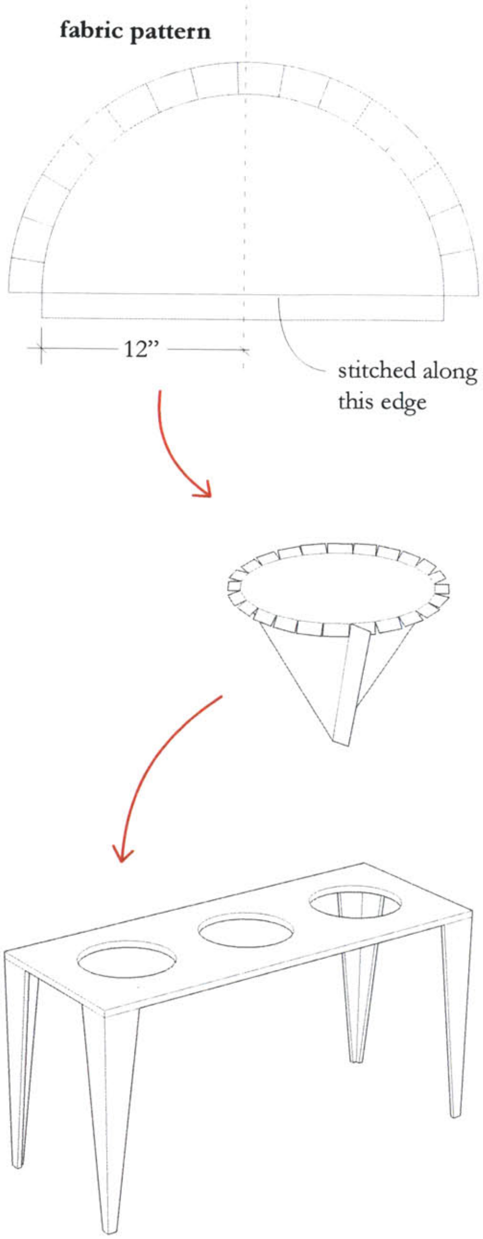


Figure 5.3.3
Fabric molding experimental setup

Final rotational forming test incorporating permeable formwork

These initial experiments looking at fabric forming took place as I continued to conduct my centrifugal forming tests. At this point I had cast four cylinders, each one an improvement on the last. I was refining the molding process but I had yet to achieve any hint of densification. I had come to the realization that I was not going to be able to produce enough centripetal acceleration to see the kinds of densification I was achieving statically in the gravity columns if I continued using a pottery wheel that had a maximum rotation velocity of 200 rpms. Because I was hesitant to seek out higher velocity devices, I decided instead to try to combine the permeable formwork I had been experimenting with at the time with rotational molding. I ended up creating a fabric lined cylindrical mold

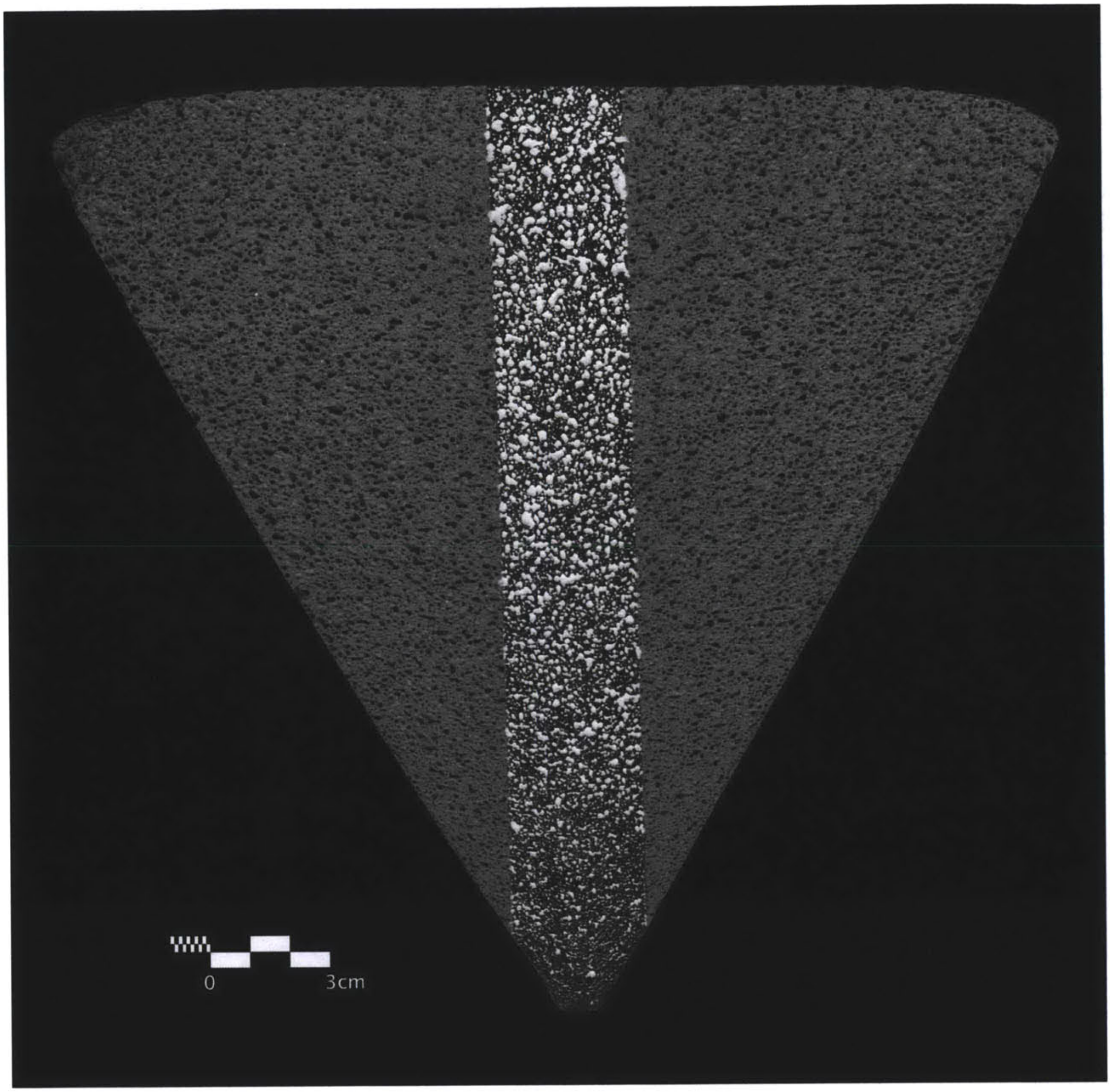


Figure 5.3.4
Image of cone #1 prepared for analysis - non permeable mold

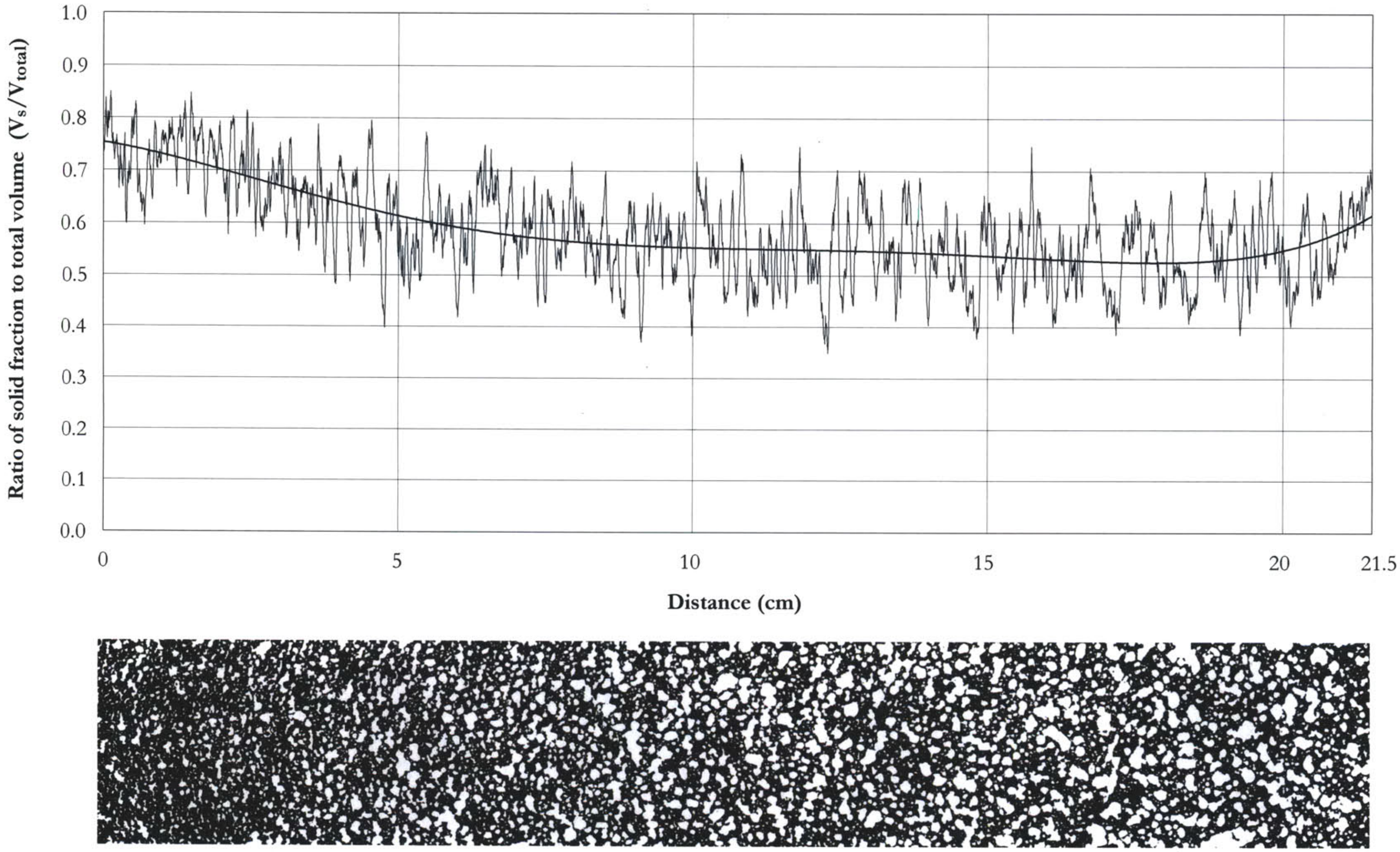


Figure 5.3.5
Image analysis of cone #1

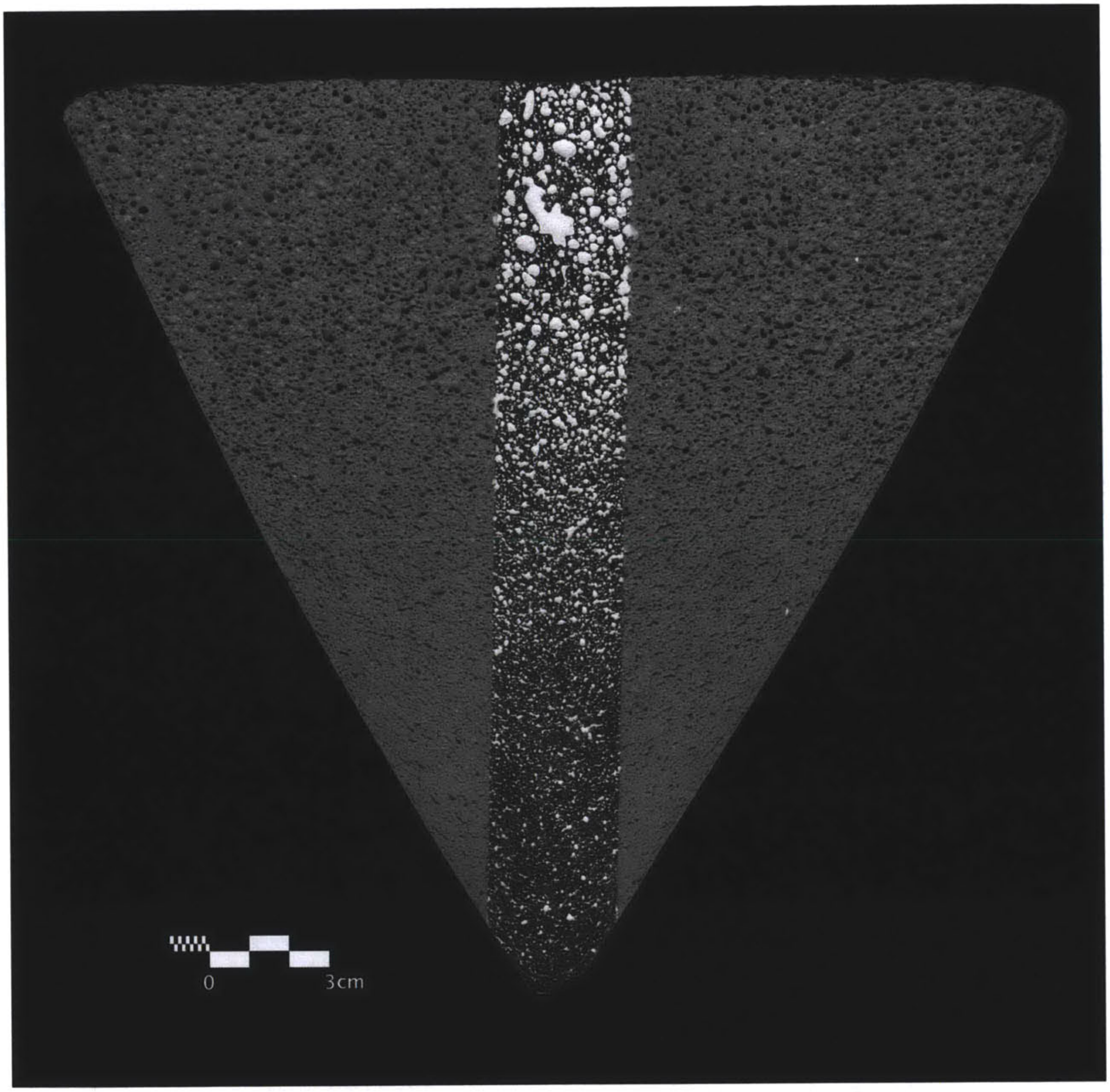


Figure 5.3.6
Image of cone #3 prepared for analysis - permeable mold

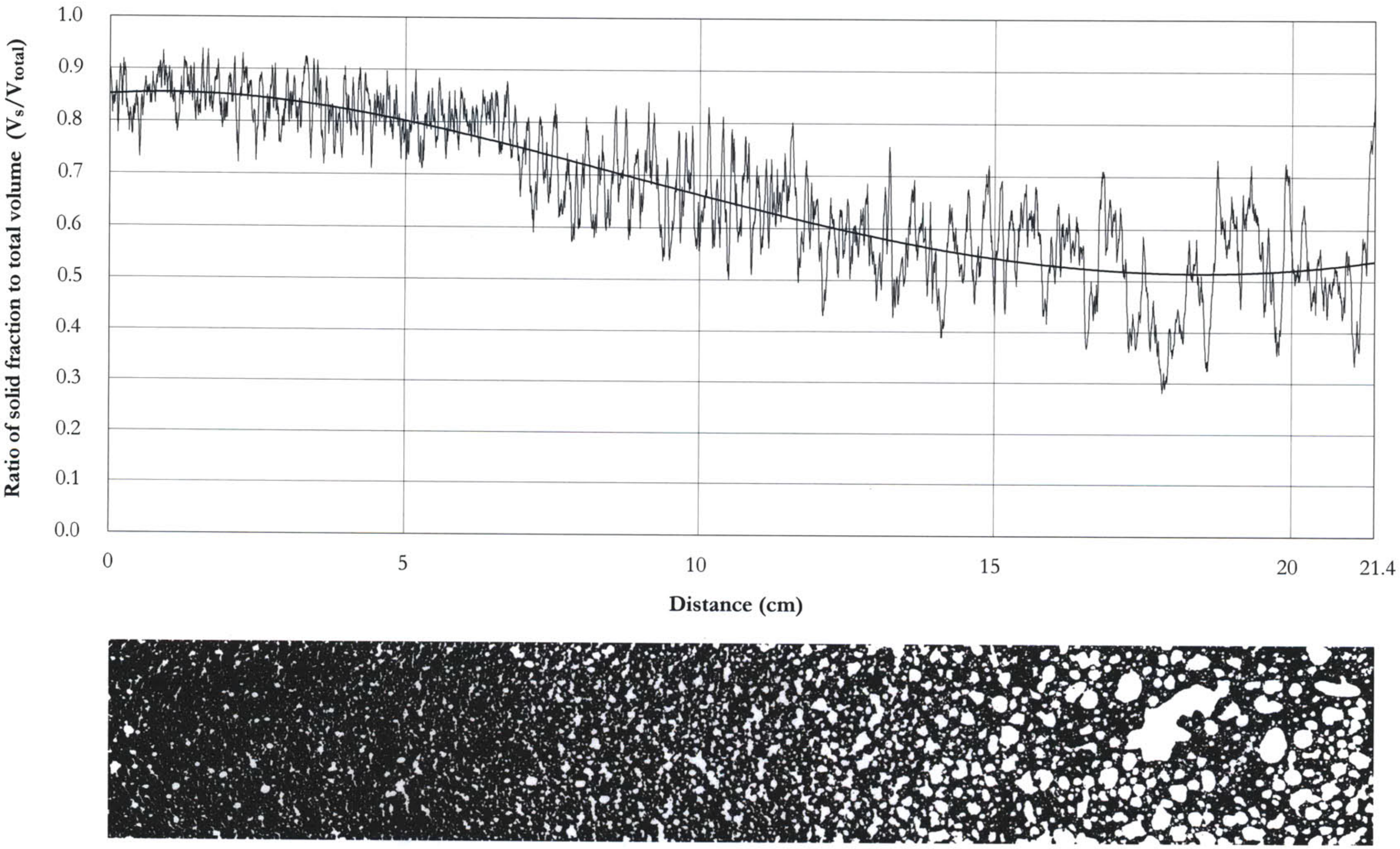


Figure 5.3.7
Image analysis of cone #3

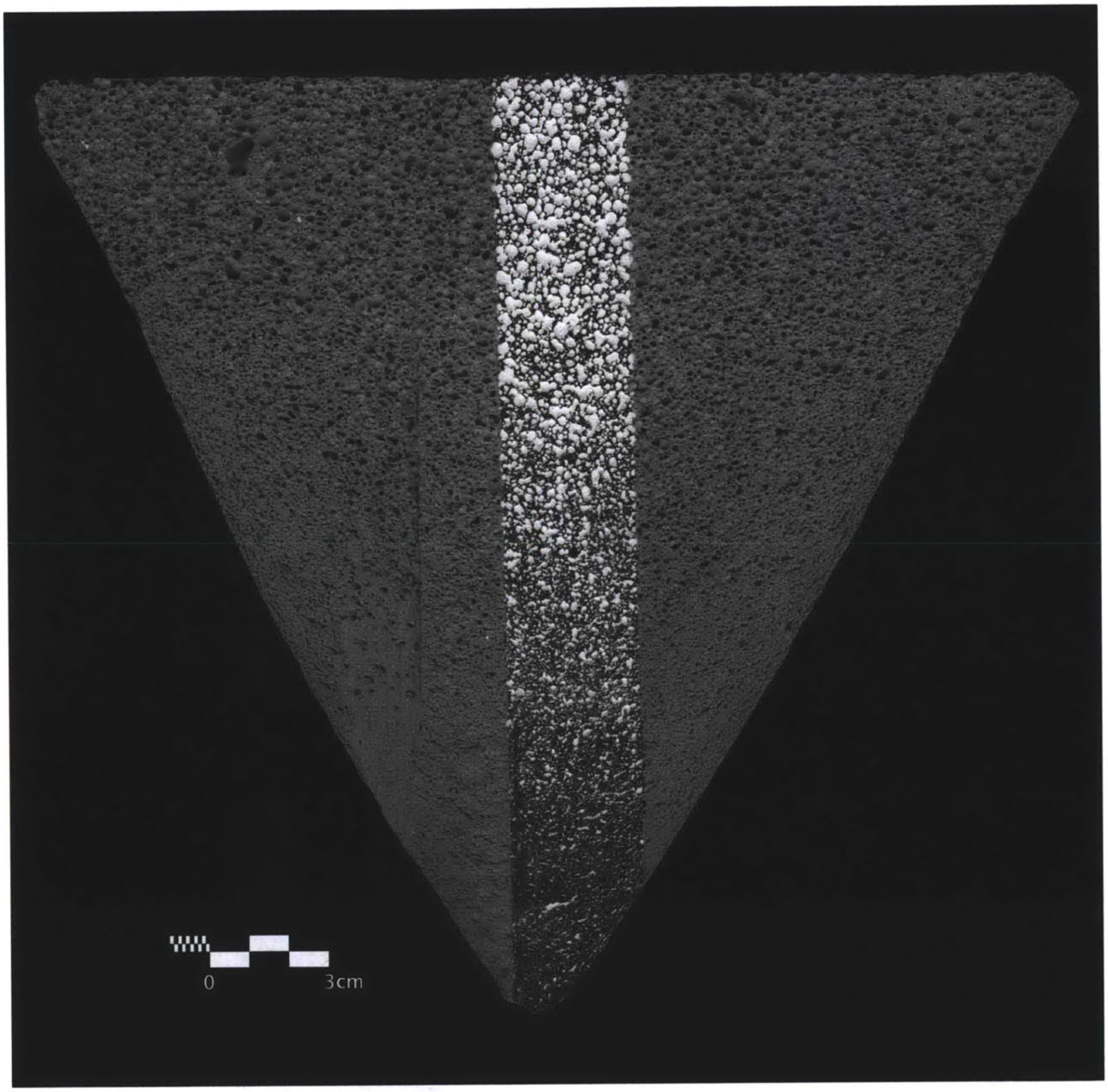


Figure 5.3.8
Image of cone #4 prepared for analysis - permeable mold with quartz sand added

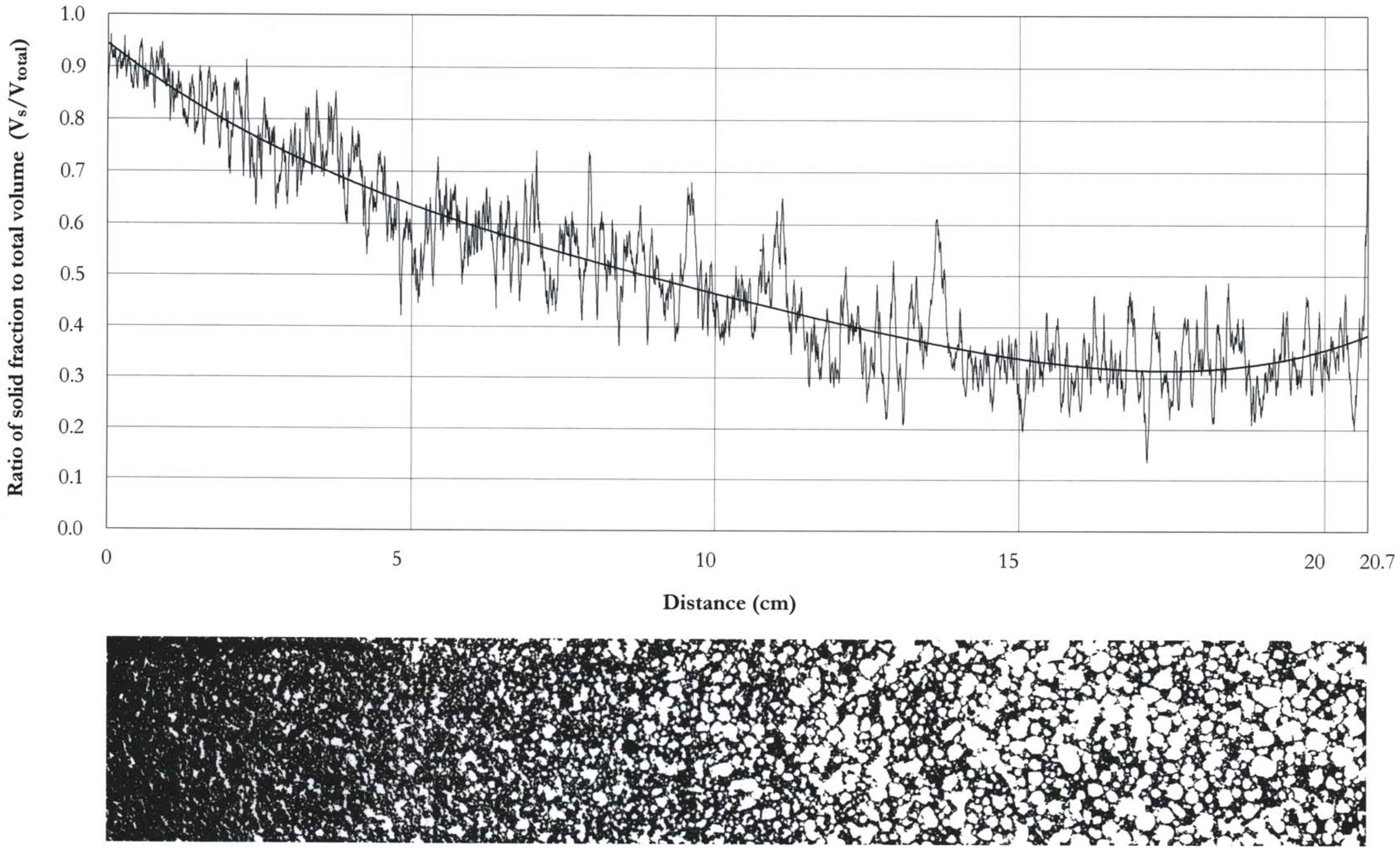


Figure 5.3.9
Image analysis of cone #4

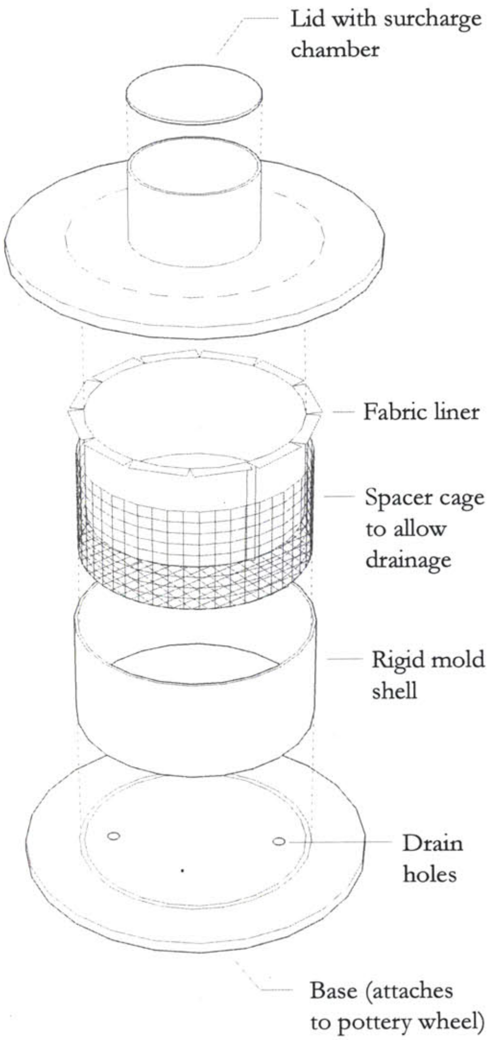


Figure 5.3.10
Final fabric-lined centrifugal mold design. See also Plate 23-27, appendix.

that I could spin on the same pottery wheel. Based on my conical fabric tests, I knew that permeable formwork had a dramatic densification effect. I hoped to see radial densification through the combination of centrifuge action and permeable formwork.

For this new mold design incorporating permeability, I constructed a rigid mold much like my earlier iterations. I then lined the sides and bottom of the mold with two layers of galvanized steel hardware cloth, with a finer mesh size positioned on the inside of a coarser mesh. These two layers of mesh essentially acted as an armature that held the cloth liner away from the impermeable rigid wall, allowing water passing through the fabric to drain down the inside of the rigid outer wall and out weep holes on the bottom of the mold. This design is illustrated in Figure 5.3.10. I tailored a cylindrical cloth sleeve out of the same finely woven cotton chintz used in the conical tests to cast cone #3. As I described in section 5.2, for this final design I also added a surcharge chamber on top of the lid in an effort to resolve some of the issues I had previously had with the expanding slurry not completely filling the mold.

This final cylinder was spun for approximately 1.5 hours at 200 rpms. About 20 minutes into the spin cycle I had to stop spinning to fix a piece of duct tape that had come loose and apply additional tape to seal up a small leak that had developed in the lid. I restarted the spin cycle after a few minutes and encountered no further problems. I collected approximately 500 mL of water during the spin cycle, which equaled about 15% of the total water used in the mix. This amounted to a similar water reduction as observed in the conical fabric test #3, which utilized the same cotton fabric.

As can been seen by looking at the exposed cellular structure (Figures 5.3.11 and 5.3.12), a distinct radial density gradient was achieved in this cast specimen, with significant densification occurring up to 2 inches in from the outside surface of the cylinder. Also visible are tangential cracks that show up in the denser region of the cylinder. These cracks are troubling because they compromise the integrity of the material. It is possible they could have been caused in part by the stoppage that occurred 20 minutes after the spin cycle began. A more likely explanation is that the cracking is a result of differential drying shrinkage due to the variation in density across the radius of the specimen. Further tests would have to be conducted to be able to come to any conclusions about origin of these cracks.

The issue of shrinkage cracking is an important one; it is one of the main questions that have come out of this research: with the introduction of variation in material composition, does the heterogeneity of the material produce insurmountable challenges related to drying and shrinkage cracks?

5.4
Absorptive Formwork Tests

Permeability and hydrostatic pressure

After conducting experiments with permeable formwork in both conical and cylindrical configurations, I was interested in establishing some metrics regarding the level of permeability that would give the best results when it came to densifying aerated concrete. In an effort to test this, I cast a series of 4 in. cubes of aerated concrete that were cast in molds that incorporated woven polypropylene meshes of varying sizes located on two sides and the bottom of the molds (Images 28 and 29, appendix). I cast five cubes in these woven meshes with mesh opening sizes ranging from 105 μm to 210 μm (Images 30-34, appendix). None of the casts showed any significant water penetration through the mesh regardless of the size of the mesh. A small amount of beading on the surfaces of the casts was visible, but cement particles were also clearly penetrating the mesh, which was undesirable.

These tests did not produce any significant densification. It was clear that no densification was produced because there was not enough hydrostatic pressure present to force any substantial quantity of water through the meshes, regardless of the size of the openings. Just as important, based on these polypropylene mesh tests, I realized that the *absorptive* nature of the cotton fabric that produced such positive results in cone test #3 and #4 was a key factor in that cloth's

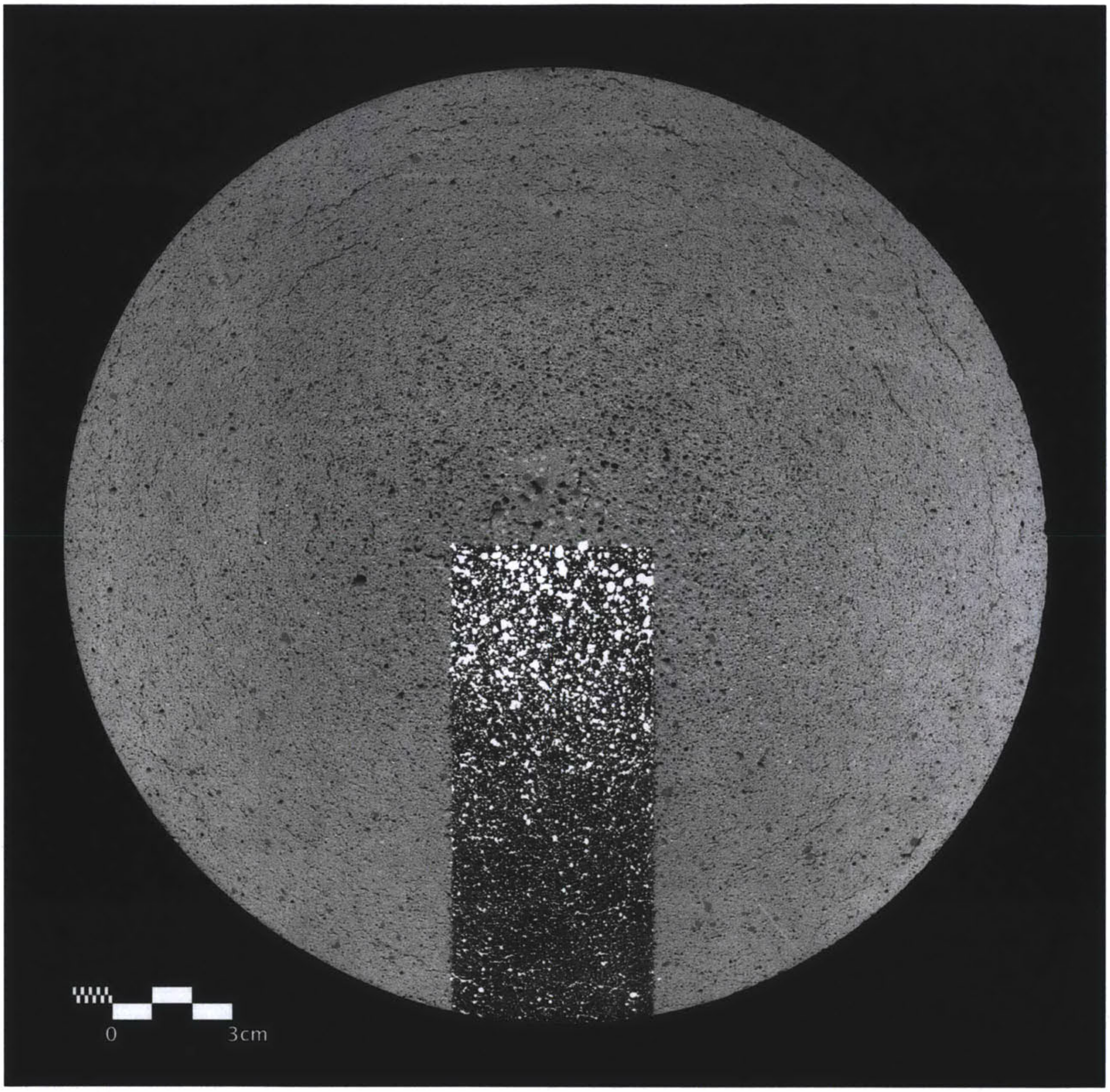


Figure 5.3.11
Image of centrifuged cylindrical casting

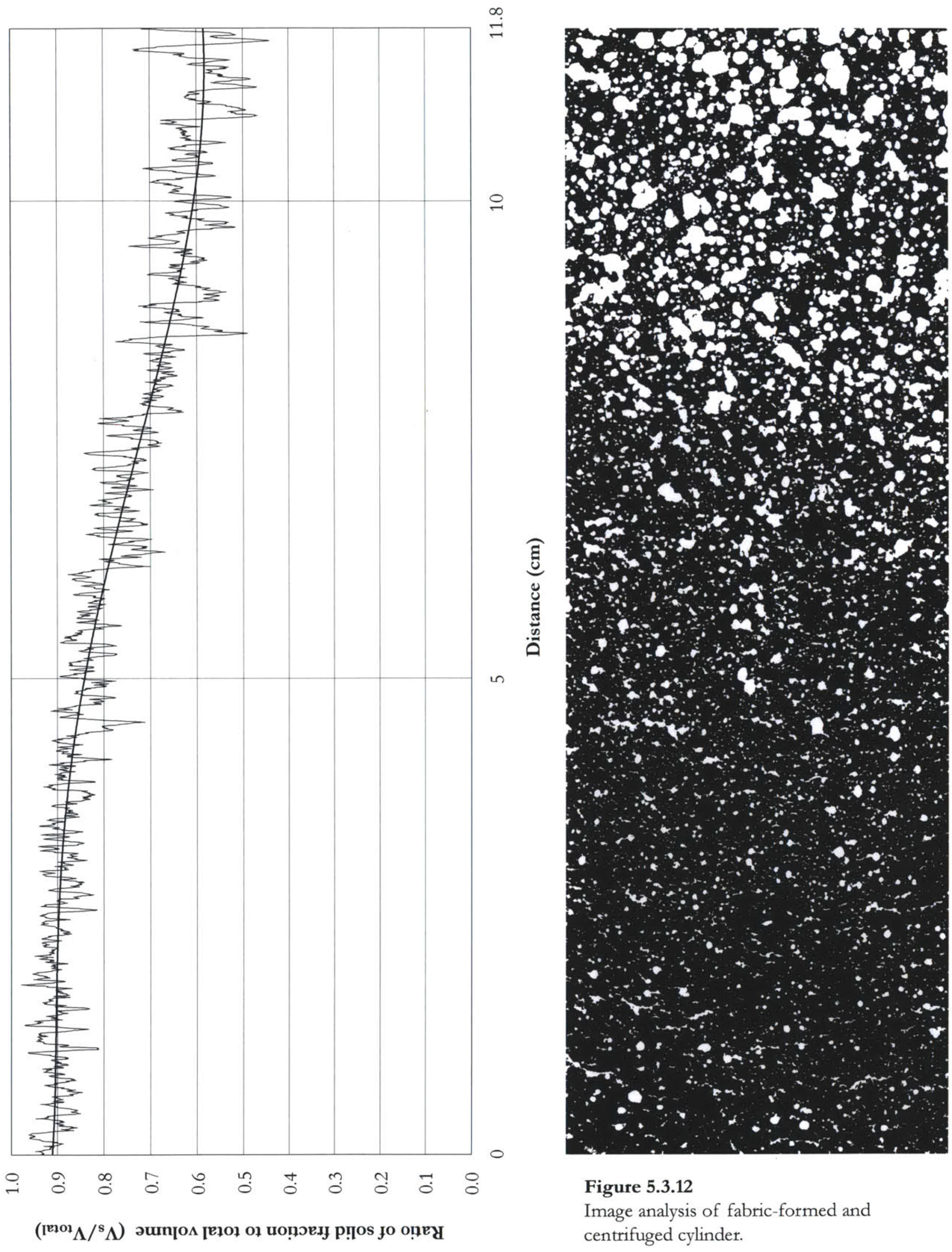


Figure 5.3.12
Image analysis of fabric-formed and centrifuged cylinder.

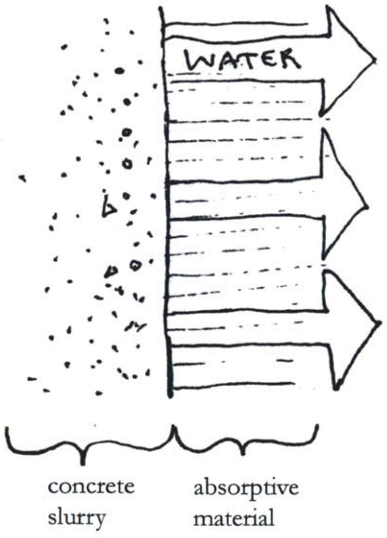


Figure 5.4.1
Absorptive molding materials

ability to wick water from the cast specimen as it was aerating. It was only after conducting these unsuccessful mesh tests that I realized that the absorptive qualities of a molding material were just as important as any level of permeability found in a textile.

Because there was not enough pressure present to force moisture out of these 4 in. cubic casts, I decided to introduce an absorptive material on the outside of the mesh in an effort to promote the migration of water out of the casting. If sufficient hydrostatic was not present in a particular configuration, I wanted to see if I could employ alternative methods for driving the moisture through a permeable membrane. To this end, I decided to see if I could couple an absorptive material with a permeable membrane, thus creating an environment where water removal could take place in the absence of significant hydrostatic pressure. This would also start to give me an idea about the interplay between permeability and absorptivity.

Casting in superabsorbent polymers (SAPs)

I first tried superabsorbent polymers packed on the outside of the same set of meshes I had used earlier in the 4 in. cubic molds (Plate 35, appendix). Unfortunately, these polymers (polyacrylates) did not actively absorb water through the meshes to the degree I had hoped. Instead, the polymers interacted at the surface of the cast and inhibited the hydration of the cement. This chemical interaction produced ammonia and caused the surface of the casts to develop a chalky film (Plate 36 and 37, appendix). At the time I did not fully understand what was occurring at a chemical level and so I figured if I just limited the exposure between the aerated concrete and the superabsorbent polymers (SAPs) to only the first few hours when the aeration took place, I might be able to minimize any negative chemical interactions between the polymers and the cementitious mix. In contrast, these first disappointing tests had been allowed to remain in contact with the SAPs for six days. I conducted a second round, only leaving the SAPs in contact with the casting for 4.5 hours. This greatly reduced the level degradation caused by the SAPs, but I still was not seeing enough absorption to create significant densification.

Based on these tests, I concluded that regardless of the types of materials I was using to try to extract water from the casting, it was clear that a certain level of hydrostatic pressure had to be present for densification to occur. I hypothesized that there needed to be present a combination of two general phenomena for meaningful densification to occur:

1. Adequate pressure build-up either statically through hydrostatic pressure or dynamically through the employment of centrifugal forces.

2. The presence of a permeable and/or absorptive material.

This hypothesis was corroborated as I continued to experiment with casting in absorbent and permeable materials. After my work with the relatively small-scale 4 in. castings, I decided to try scaling up to reintroduce significant hydrostatic pressure into the process while at the same time further exploring the use of absorptive casting materials.

I first tried casting with SAPs at a larger scale. I had located a supplier that produces hydrophilic polyester fabric that is impregnated with cross-linked polyacrylate superabsorbent polymer particles. This product was rated to absorb 2 quarts of water per square foot of material. I hoped to see improvements in levels of absorptivity by using this material in conjunction with larger-scale castings. The inside dimensions of the mold were 12 in. x 4 in. x 14 in. (Figure 5.4.2), with the fabric stretched on the two narrow sides of the mold. As can be seen in the plan cut through the center of the casting (Figure 5.4.3, 5.4.4), the combination of an absorbent material and the level of hydrostatic pressure present in a cast of this size produced significant densification (as well as deflection of the fabric, which resulted in the curved profile at those locations). Also, because the SAP particles were contained within the fabric and only exposed to the concrete for 20 hours for this casting experiment, the surface quality was not greatly compromised by the chemical interaction between the SAPs and the concrete.

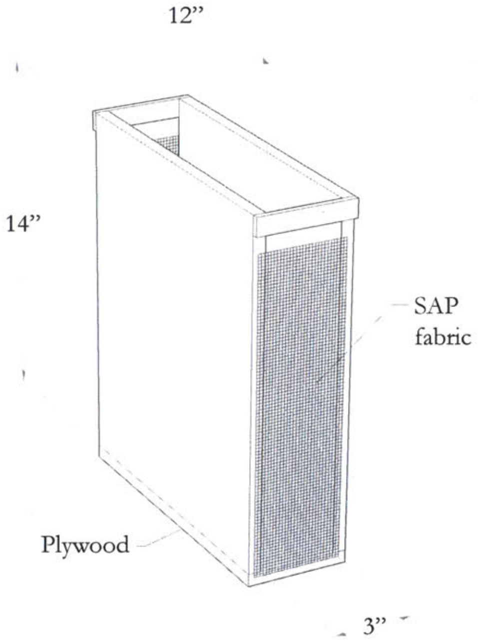


Figure 5.4.2
Super-absorbent-polymer (SAP) fabric mold design

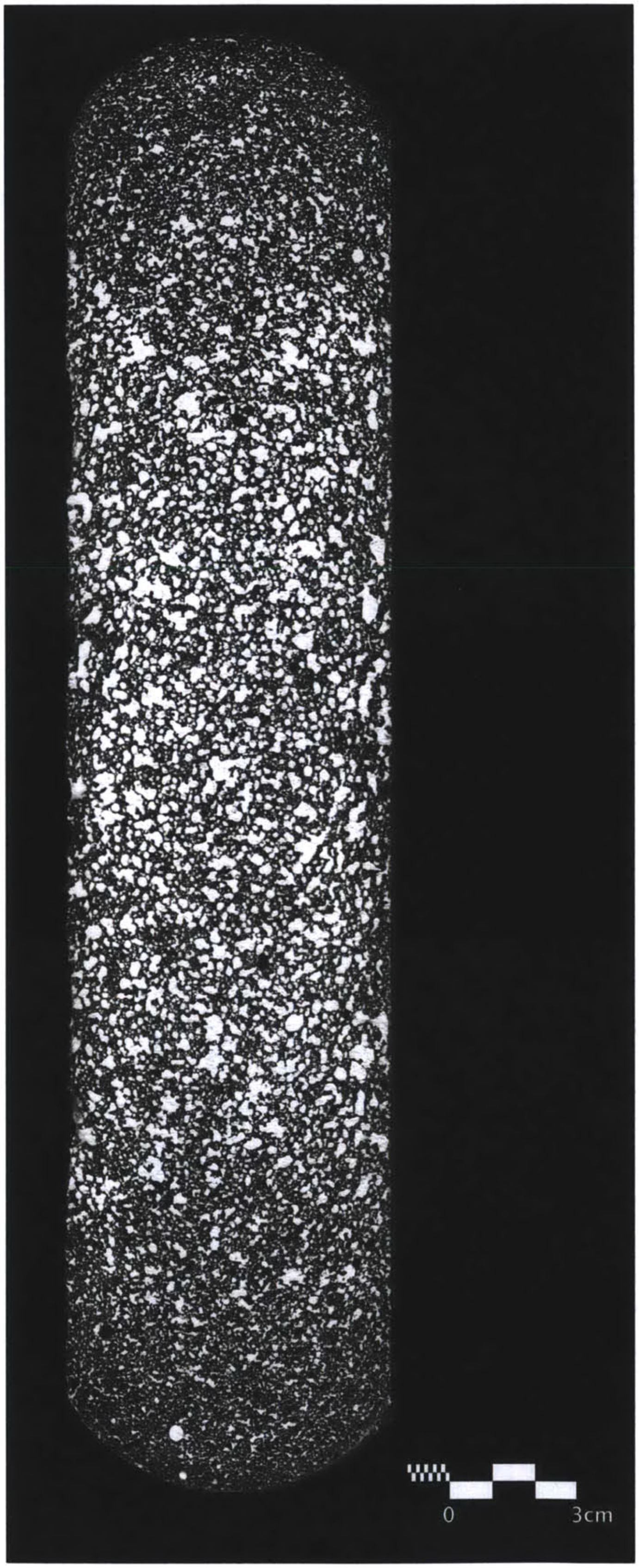


Figure 5.4.3
Image of SAP fabric cast

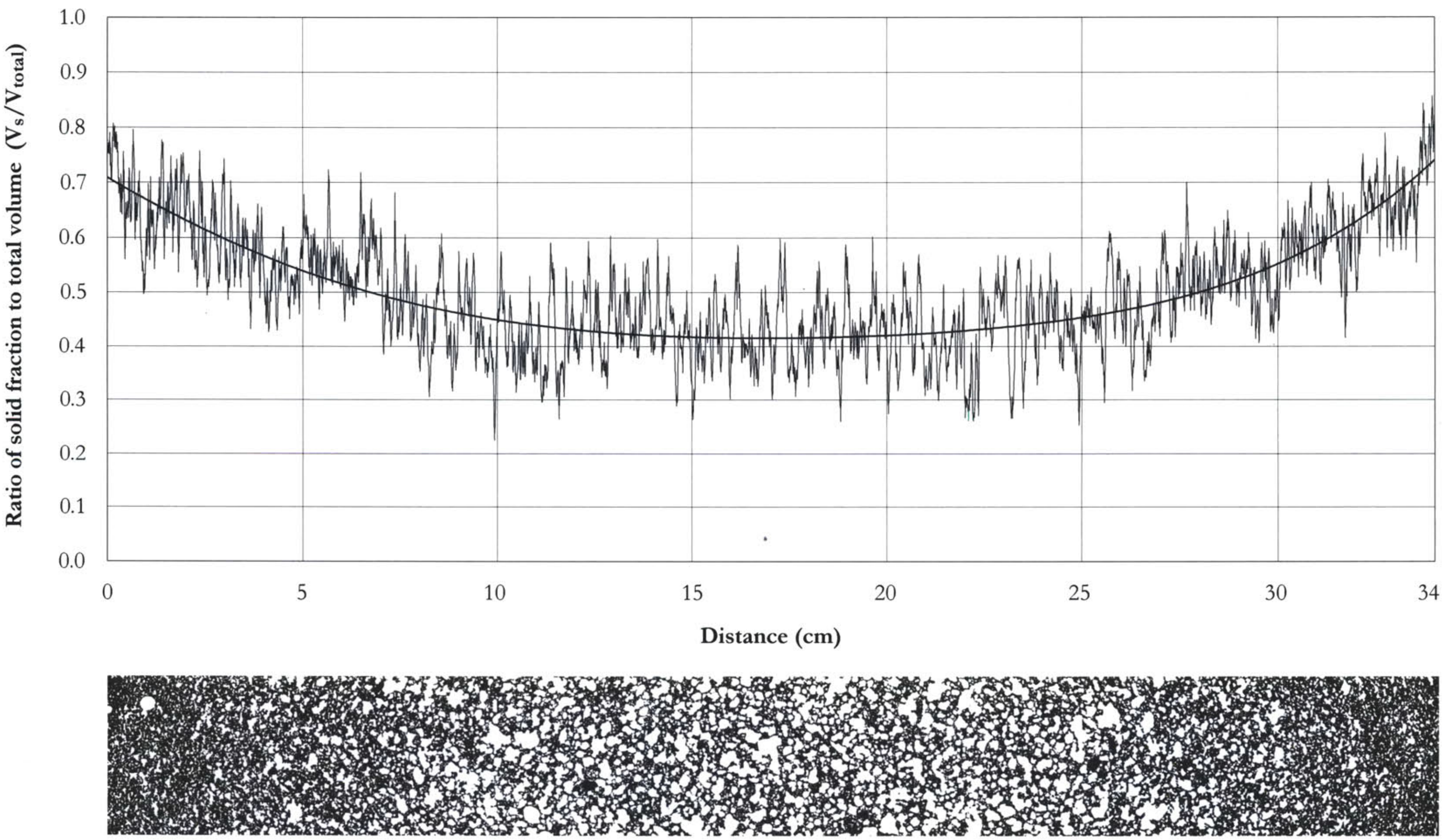


Figure 5.4.4
Image analysis of SAP fabric cast

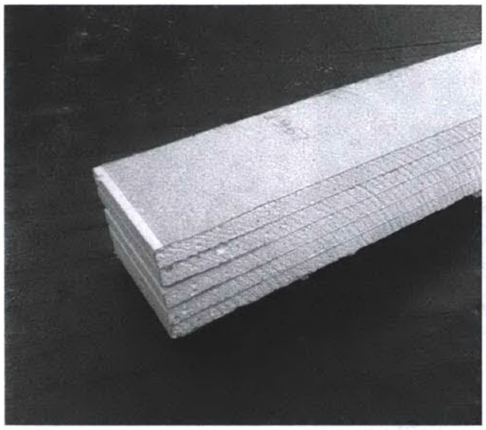


Figure 5.4.5
Gypsum wallboard by-product used to make gypsum molds.

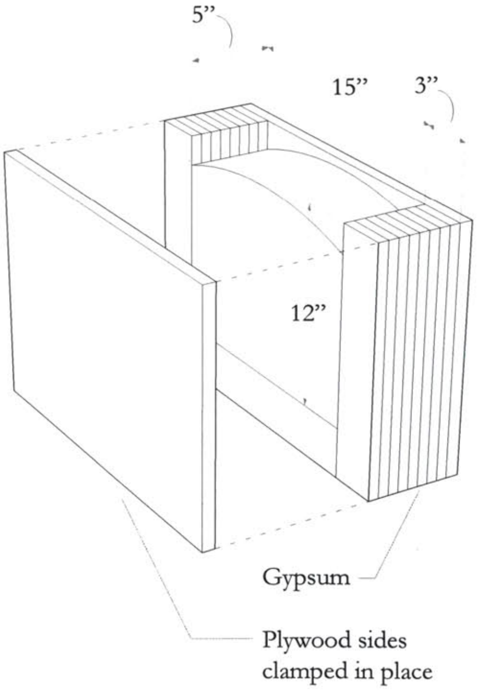


Figure 5.4.6
First gypsum mold design

Casting in gypsum

During this same time period I became interested in trying out other materials with absorptive properties that might effectively wick moisture out of my casts during the aeration process. I had been interested in looking at gypsum for a while, but did not try using it as a casting material until I came across a gypsum waste product that is a byproduct of the supply chain of traditional gypsum wallboard. Gypsum wallboard is shipped on pallets oriented horizontally. Between every dozen or so sheets that are stacked, spacers are inserted to allow ease of removal via forklift. These spacers are made from the same gypsum wallboard cut into strips and stacked (Figure 5.4.5). These discarded pieces of gypsum were perfect for constructing dimensionally stable rigid molds with exposed gypsum faces.

The first gypsum mold I constructed followed a similar design as the SAP impregnated fabric mold, but with the addition of an absorptive surface on the bottom of the mold (Figure 5.4.6 and Plate 38 and 39, appendix). The results from this test appeared to be very promising as soon as I had poured the slurry into the mold. Upon contact with the surface of the gypsum, the slurry quickly changed consistency and thickened. As the slurry began to foam, it was obvious that in the regions adjacent to the gypsum, foaming was not occurring at nearly the same rate as the rest of the casting. As can be seen in Plate 40 (appendix), the slurry at the sides has not expanded while the majority of the slurry not in proximity to the gypsum has begun rising at the normal rate.

By looking at a sectional cut through this specimen, one can observe a high degree of densification that penetrates quite deep into the cast. This densification has been characterized in the vertical direction here (Figure 5.4.7, 5.4.8), but by looking at figure 5.4.7 it is clear that densification is fairly consistent adjacent to all surfaces that were in contact with the gypsum, regardless of the depth within the cast. This indicated to me that the level of hydrostatic pressure required to achieve densification was quite low when using gypsum to remove water during the aeration process. Despite these very promising results, the gypsum had negative effects when it came to the quality of the surface of the concrete directly in contact with the gypsum. The gypsum appeared to have dried out the concrete at the interface to a level where it inhibited hydration of the cement. This resulted in a surface that was cracked and flaky. Also, this casting exhibited internal cracks much like those seen in the centrifuged radial fabric cast. The cracks in the gypsum cast seem directly related to the variation in composition caused by the gypsum. One can see cracks that emanate from the interface between where the slurry did not foam and the foamed material that rose and folded back on top (Figure 5.4.7), much like bread rising over the top of a bread pan (Plate 41-42, appendix).

Development of a family of prototypes

After conducting this initial gypsum casting experiment, I began to think about the interesting configurations that might be possible when using these pieces of waste gypsum to produce density gradients. Up until this point in my experimental work, I was mostly concerned with testing out various methods for producing density gradients within the material. During this process, I was always thinking about the potential application for these techniques, but my first objective was to develop robust methods. Now that I had begun to establish a number of promising techniques for producing gradients, I started to focus on the morphological possibilities when employing the various techniques. Up until this point, the only castings I had envisioned having direct application as structural building components were the radial gradient cylindrical castings, which I imagined being used as columns that were optimized to resist buckling or bending.

As I have attempted to emphasize in the description of the work thus far, there are numerous limitations and constraints associated with all of the techniques I have investigated. To generalize, the core controlling parameters are *orientation* and *scale*. These two parameters constrain what geometries and internal density profiles one can produce. As I had discovered when doing the 4 in. cubic castings, producing densification requires a certain *scale* to provide adequate fluid pressures within the cast. I now knew gradients could

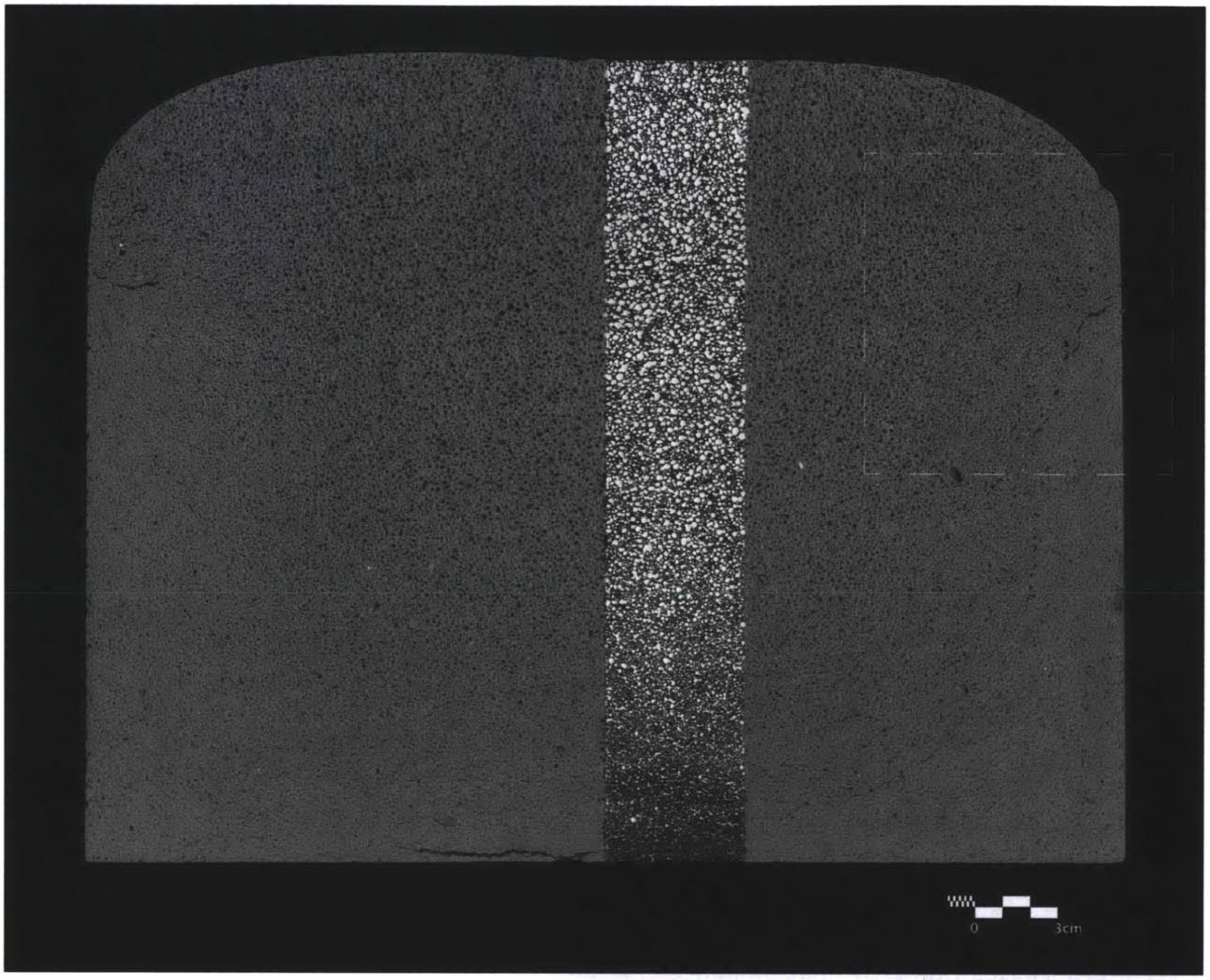
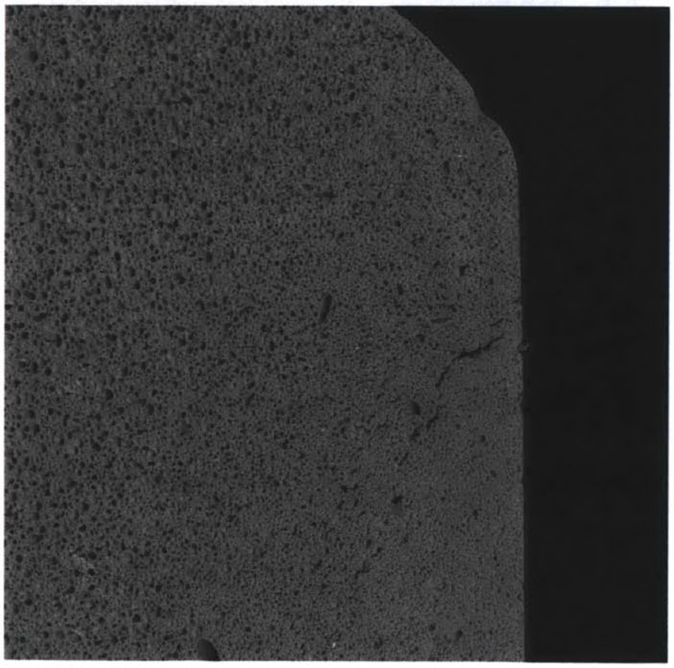


Figure 5.4.7
Image of first gypsum casting



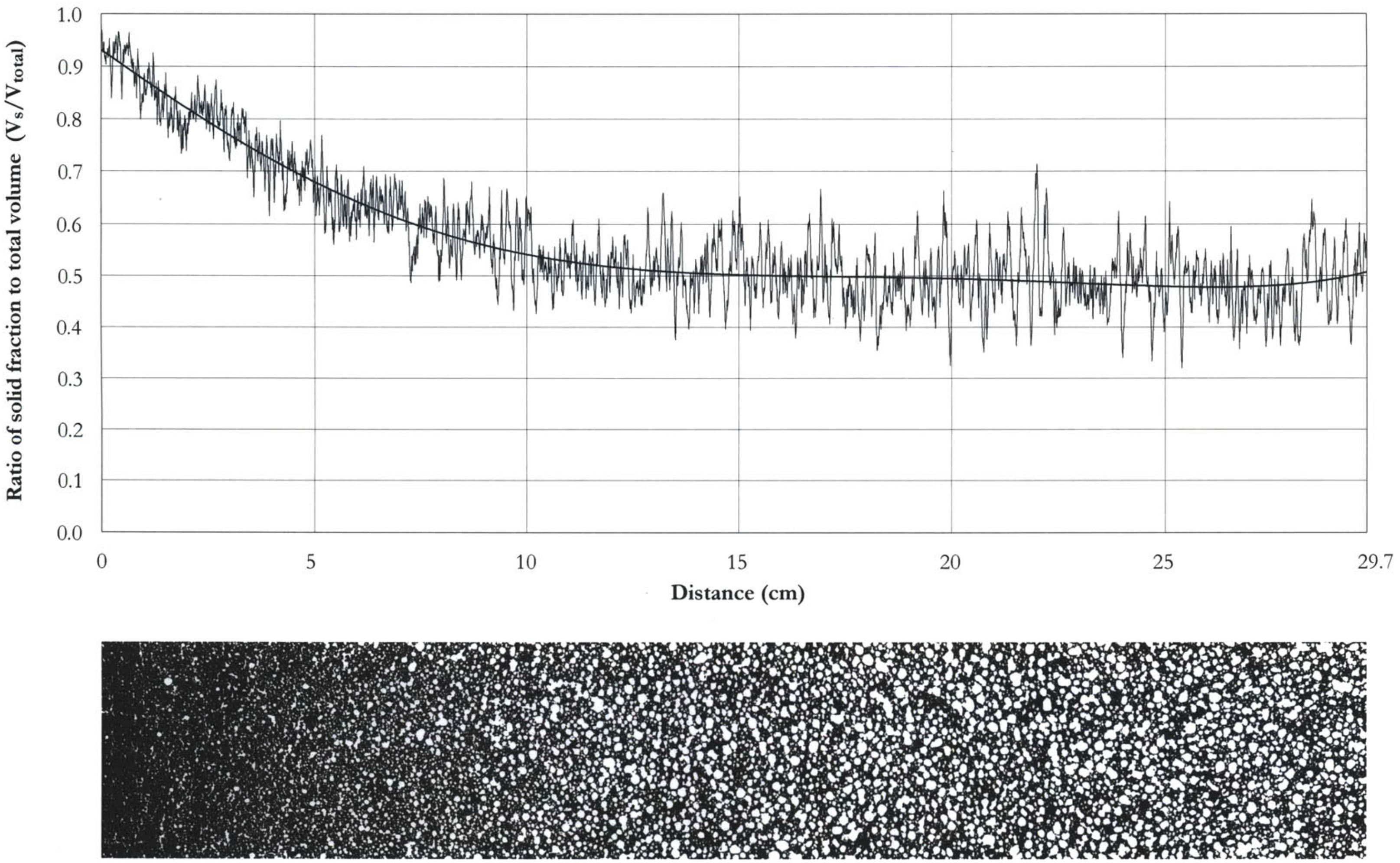
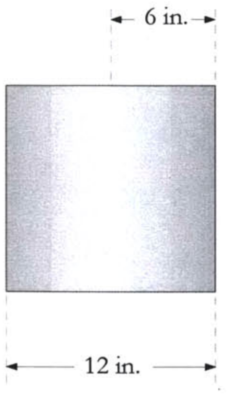


Figure 5.4.8
Image analysis of first gypsum cast

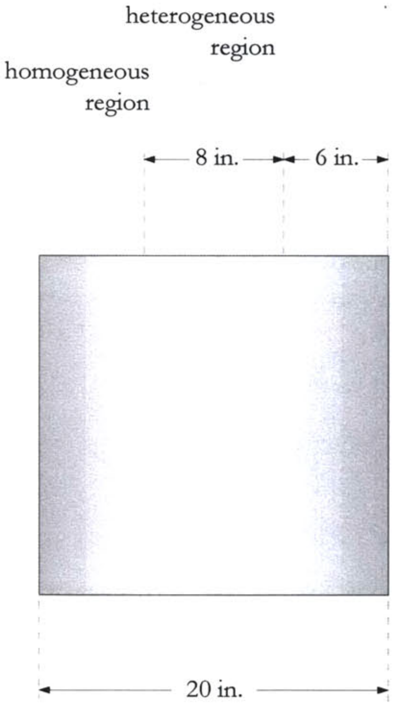
only be produced in castings at scales on the order of tens of inches. I also knew that the gradients themselves were at a scale on the order of a few inches. So, as a rule, these techniques can only be employed to create a density gradient along surface zones in a cast element of a certain scale, where the density transitions from its highest at the surface to a baseline low density that would be consistent throughout the interior of the cast element if that element became much larger than the scale of the gradient (Figure 5.4.9).

In addition to the constraints related to scale, casting in a gravity environment necessarily means that *orientation* plays a role in any casting. There is always a "top" surface that isn't going to be densified in any of the cast objects I can produce. In additional, there will also always be a baseline vertical variation in density due to the variation in hydrostatic pressure in a cast. For example, the radial gradient I achieved in plan in the cylindrical casting I describe in section 5.3 is overlaid on a vertical variation in density due to the baseline pressures associated with gravity. Unless I employed something along the lines of a multi-axis roto-molding device or deployed the material in a manner analogous to the injection molding of thermoplastics, I was always going to have to deal with a relationship between the orientation of the element when it was cast and the resulting distribution of densities (As a side note, both multi-axis roto-molding and injection molding would necessitate a drastic increase in complexity in the production process when applying them to a precast concrete production model). The orientation of the element when it is cast can of course be different than its ultimate orientation when it is used in a construction assembly if one is imagining a precast production model, but regardless, it is critical to spell out these constraints before diving into the potential morphologies.

To illustrate this dynamic between scale and orientation, I will describe my most recent attempts at producing a building component prototype utilizing density gradients. Because I was excited about the potential for gypsum to produce densification, I began thinking about ways in which building components could be cast using this material as an "active formwork."



a. continuous variation through section



b. variation only occurs in the first six inches from the surface

Figure 5.4.9
Density gradients in relation to the scale of a cast element

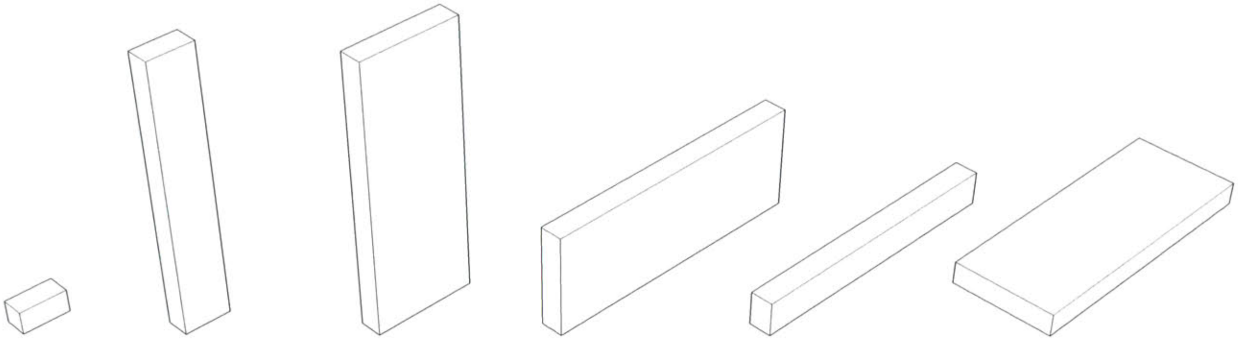
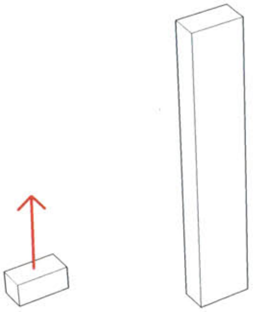


Figure 5.4.10
Morphological categories

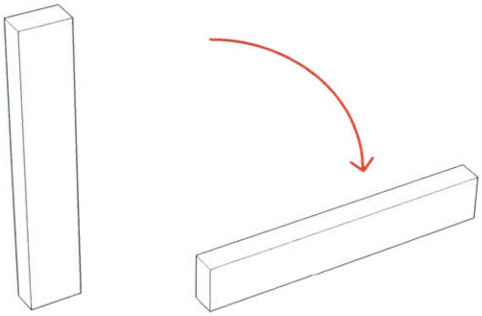
First, to step back a bit and give some context to this prototype work, I want to establish the basic morphological categories that generally interest me when thinking about introducing density gradients in building components. These categories are the block, column, panel, beam, and slab (Figure 5.4.10). This categorization is a broad way to group rectangular prismatic geometries as their proportions and/or orientation are altered. Conceptually, a column and a beam can be viewed as the same thing, just with one rotated 90 degrees from the other. The same can be said for the relationship between a wall panel and a floor slab. When looking at transformations in proportion, a column or beam can be conceptualized as an elongated block (Figure 5.4.11). Things become interesting when we realize that orientation is critical in the production process in addition to the final orientation of the cast piece. If one is trying to introduce variations in density to these different categories of components, the ability to create these gradients is limited by the techniques available for each orientation and geometry.

These categories of components can be produced more or less easily depending on the type of technique one employs and the configurations of density one might desire. I have imagined, based on the current level of development for the types of techniques I have developed for this thesis, a set of associations between geometries, orientations and density distributions. Figure 5.4.12 shows a list of variable density components. Of course there are countless iterations when one combines configuration of internal density

Figure 5.4.11
Proportion and orientation

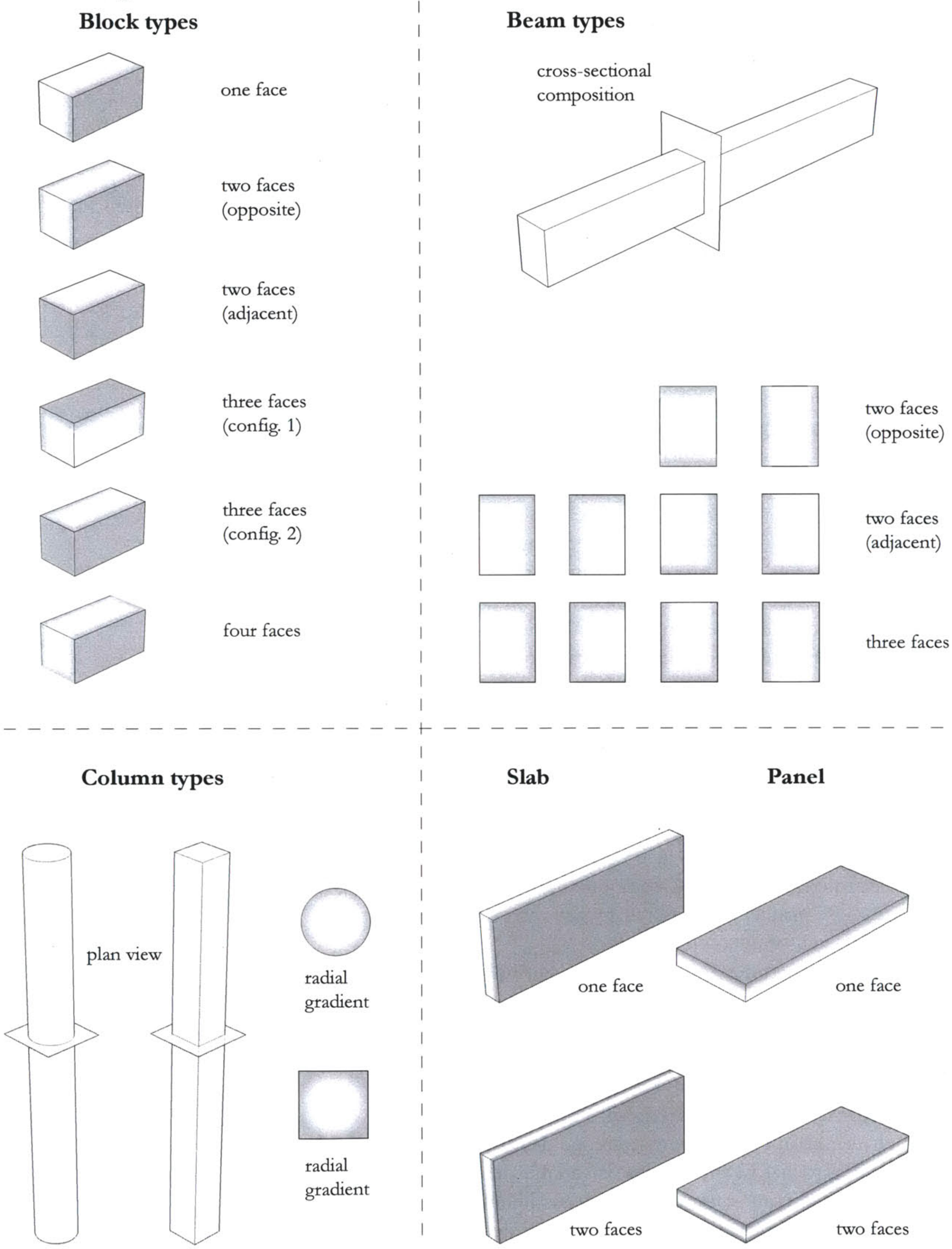


change in proportion:
a block becomes a column



change in orientation:
a column becomes a beam

Figure 5.4.12
Matrix of configurations



gradients with orientation. All of the illustrated examples I am showing in Fig. 5.4.12 are configurations and orientations I deem to have potential useful value.

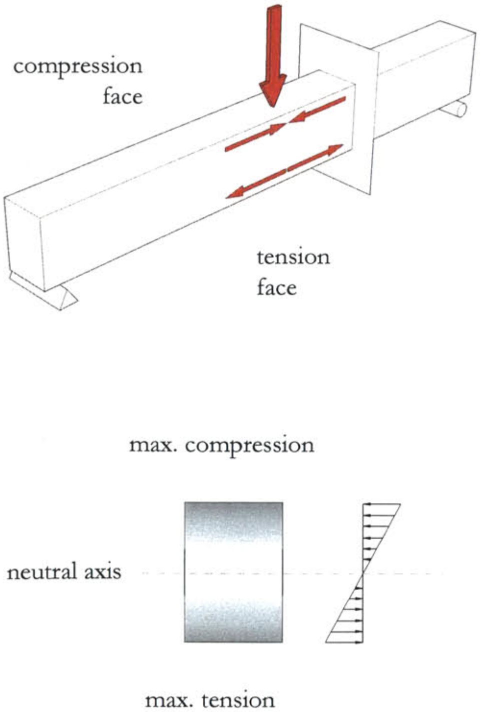
Case study: a gradient density beam

Because of my limited time and resources, I decided to produce a single prototype that I could start to use in an effort to interrogate this "menu" of morphologies I was envisioning. I wanted to see how these ideas might work in practice and hopefully demonstrate their power and flexibility by producing a successful prototype.

I decided to work with the beam morphology for a few reasons. First, I wanted to be able to cast at a reasonable scale because of equipment and space limitations. Because a simple rectangular beam does not vary along its length when conceptualized in its most basic form, I knew that I could cast a short beam as a proof of concept that would apply to a beam of any length. Essentially, for this first prototype I was interested in its cross-sectional composition, not its composition along its length. Variation along the length of a beam is a very important parameter for beam design, and I will discuss the possibilities in Chapter 6, but for this prototype I wanted to constrain my experimentation to the sectional composition of a beam. I also chose the beam morphology because it is conceptually situated in the middle of my matrix of morphologies outlined in Figure 5.4.10, thus providing maximum application to the other morphologies. If I tried something with the beam, it had the greatest possibility for translation to the other morphologies: a beam is just as easily an elongated block or a thin slice of a slab.

Based on the chart outlining the casting possibilities in the previous section, I decided to cast a beam that had variation in density in the vertical orientation, with the highest density occurring at both the top and bottom surfaces of the beam. I chose this design because it dealt with gradients only along the vertical axis, keeping the design relatively simple. I was also inspired by the concept that the distribution of material (via density) would be directly associated with the distribution of the elastic stresses found in a homogenous beam when that beam is loaded in a typical manner

Figure 5.4.13
Distribution of forces in a beam in bending



(either with a uniformly distributed or point load, both producing a bending moment in the beam and the characteristic stress profile). By distributing density in this manner, I was creating a beam section that had a higher *moment of inertia* and thus a greater ability to resist bending than the same geometry beam of uniform density. The increased ability to resist bending associated with a higher moment of inertia is the reason why beams are oriented vertically and why I-beams are common in the design of structural steel members. The more material you can distribute farther from the neutral axis of a beam in bending, the better the beam will be able to resist that bending. This relationship is illustrated in Figure 5.4.14. In my case, instead of changing the overall geometry of the cross section of the beam, I wanted to change the distribution of material within the *same* geometry (Figure 5.4.15).

In a certain sense, this beam prototype was an idealized look at beam design. Throughout my research, I had not investigated bar or fiber reinforcement, but tensile reinforcement is critical in any structural design for a concrete beam. For this prototype, I wanted to produce a density gradient that could be seen as a design that could easily be incorporated with tensile reinforcement design down the road. The idea for this design was that the dense top surface would be present to deal with the high compressive forces found at the top of any beam in bending. In the dense region on the bottom of the beam where tensile forces dominate, reinforcing bars could be located in this dense concrete, providing a more robust material for bondage between the reinforcing bars and the concrete.

I cast this first beam prototype in a gypsum mold illustrated in Figure 5.4.16 (see also Plate 43-46, appendix). As can be seen in the illustration, the beam was cast in a different orientation from the one intended for its final use. This was dictated by the casting constraints. I wanted a dense top and bottom surface, but because of my casting technique, the casting had to reoriented to allow for a configuration where two opposing surfaces could be densified using an absorptive material such as gypsum. This beam prototype was a success in that the finished element contained a dramatic gradation in density along its vertical axis (Figure 5.4.17, 5.4.18). After it was demolded, the foamed

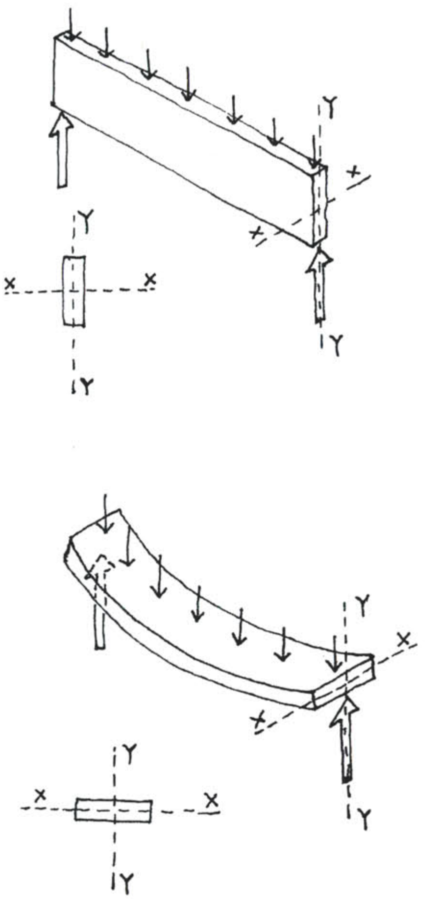


Figure 5.4.14
The effect of orientation on a rectangular beam in bending

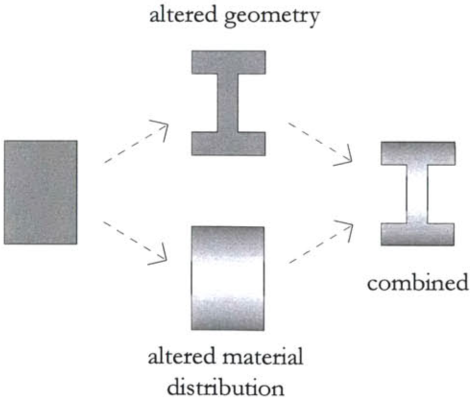


Figure 5.4.15
Two ways to think about distributing material

top of the beam was trimmed and the final prismatic shape with integral density variation was apparent (see Images 47-49, appendix). The gradients I was able to achieve in this prototype were exciting, but there still remained the problem of poor surface quality due to the interaction at the interface between the gypsum and the aerating slurry (Plate 48, appendix).

In an attempt to solve this problem of surface interaction with the gypsum, I cast a second beam, but this time I introduced a fabric liner in the hopes that a liner might reduce some of these negative effects (Plate 50 and 51, appendix). This second beam showed marked improvements in surface quality on the densified top and bottom faces of the beam (Plate 52). This final beam prototype, cast in a fabric-lined gypsum mold, was tested in a three-point bending frame (see Section 5.6). To determine the range of densities within the beam, I analyzed a sectional slice of the beam after it had been loaded to failure (Figure 5.4.19, 5.4.20). Cubic samples with outside dimensions of one inch were cut from the bottom surface of the beam as well as the centerline. These samples were weighed and the dry density was calculated. The density within the beam ranged from 1,190 kg/m^3 at the extreme fibers to 757 kg/m^3 along the neutral axis of the beam.

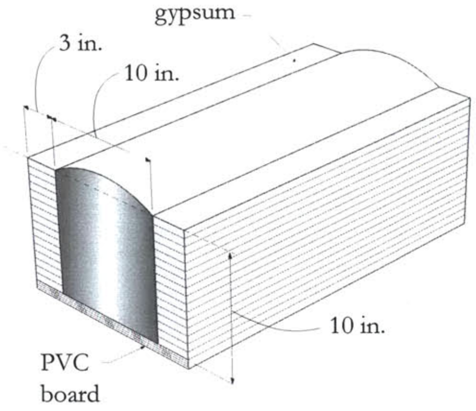


Figure 5.4.16
Gypsum mold design for first beam prototype

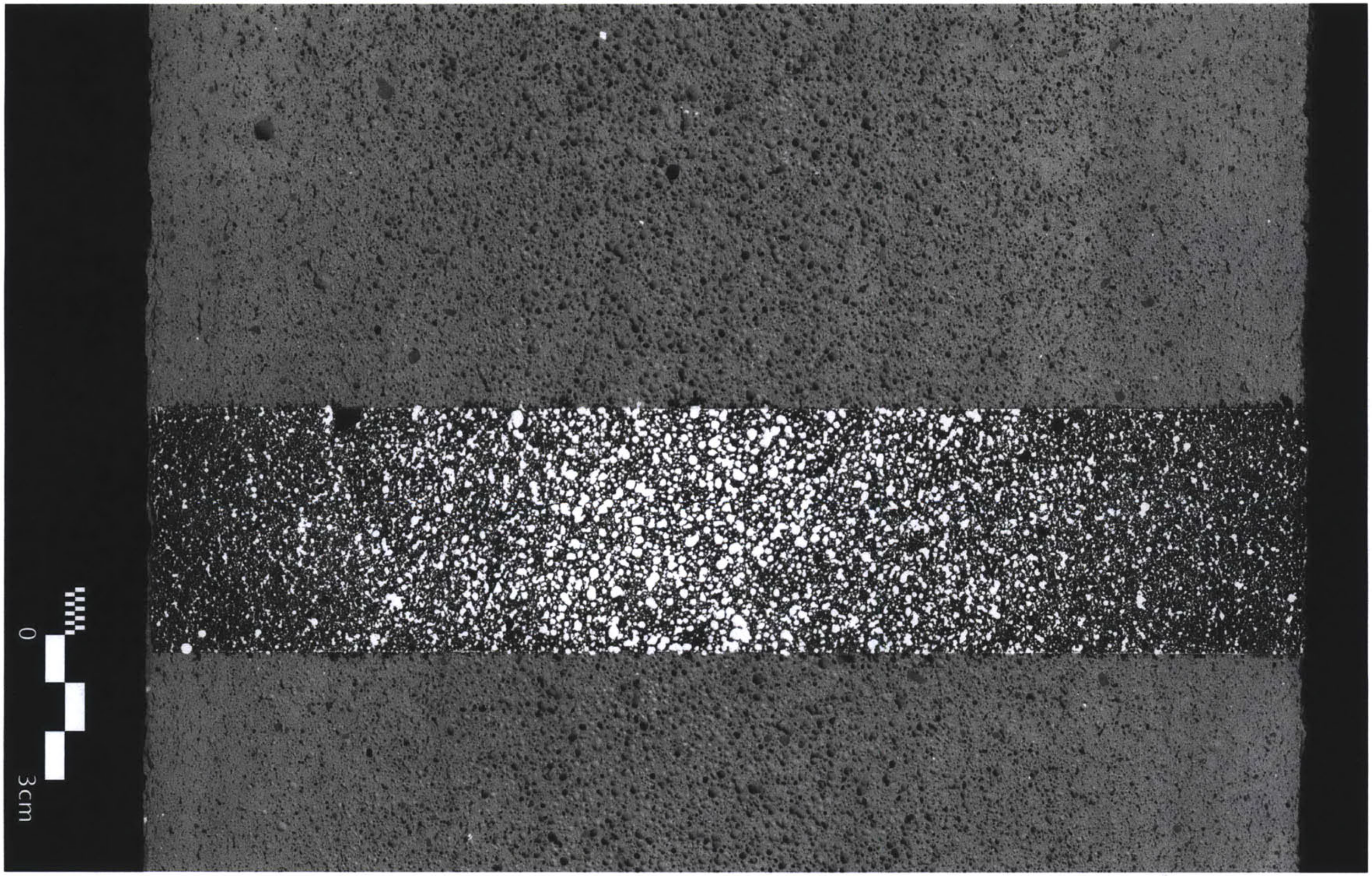


Figure 5.4.17
Image of first gypsum beam prototype

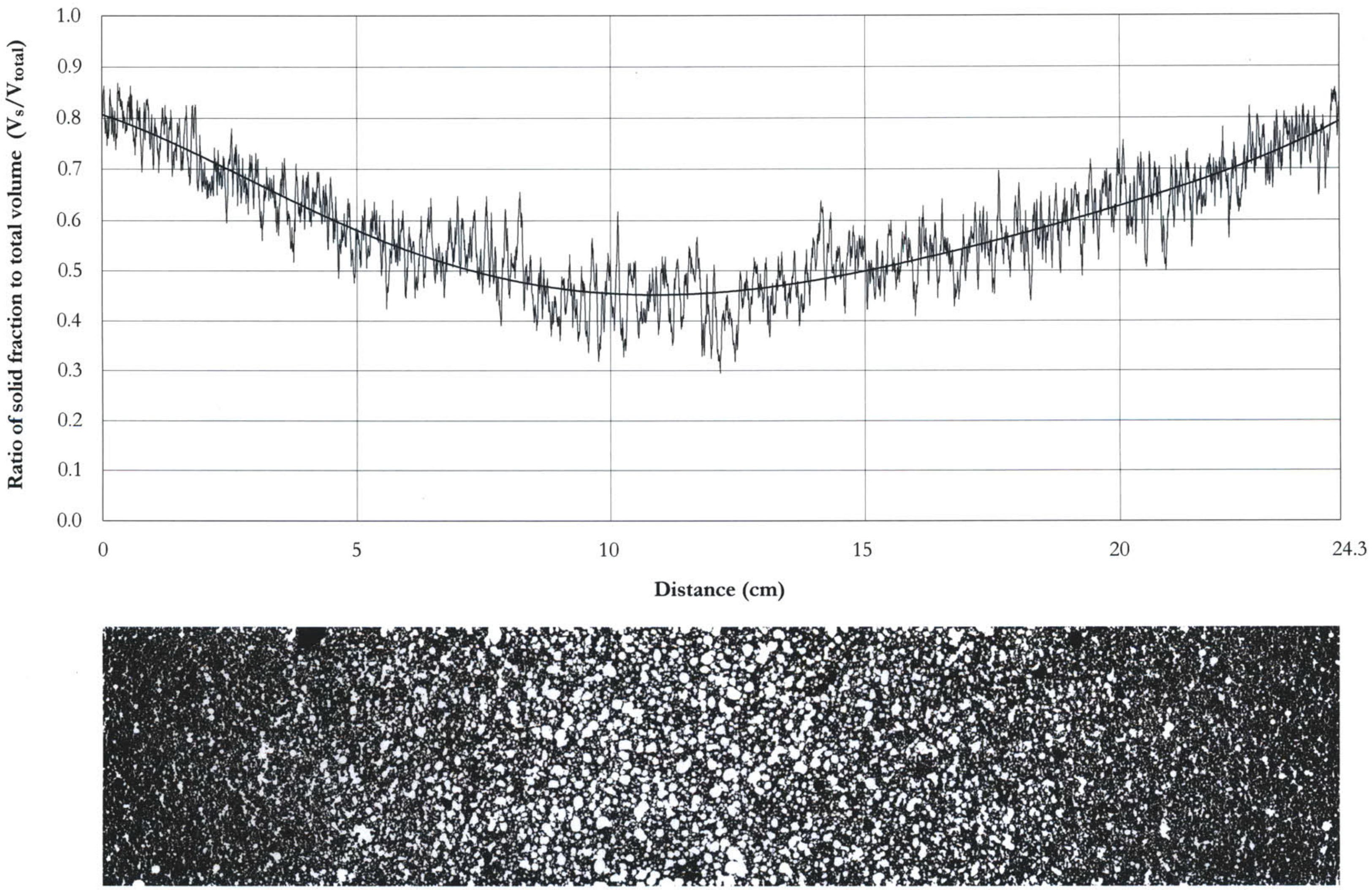


Figure 5.4.18
Image analysis of first gypsum beam prototype

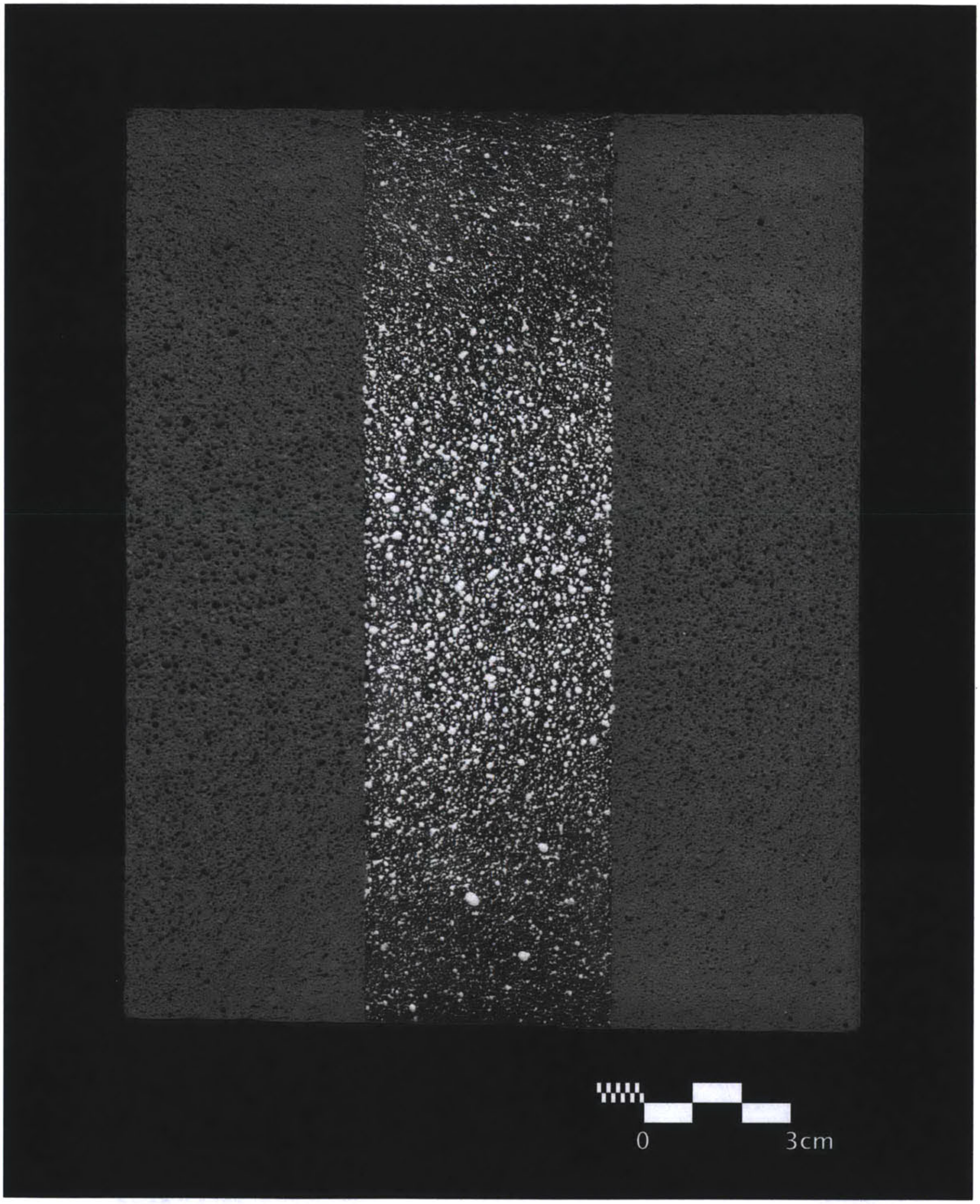
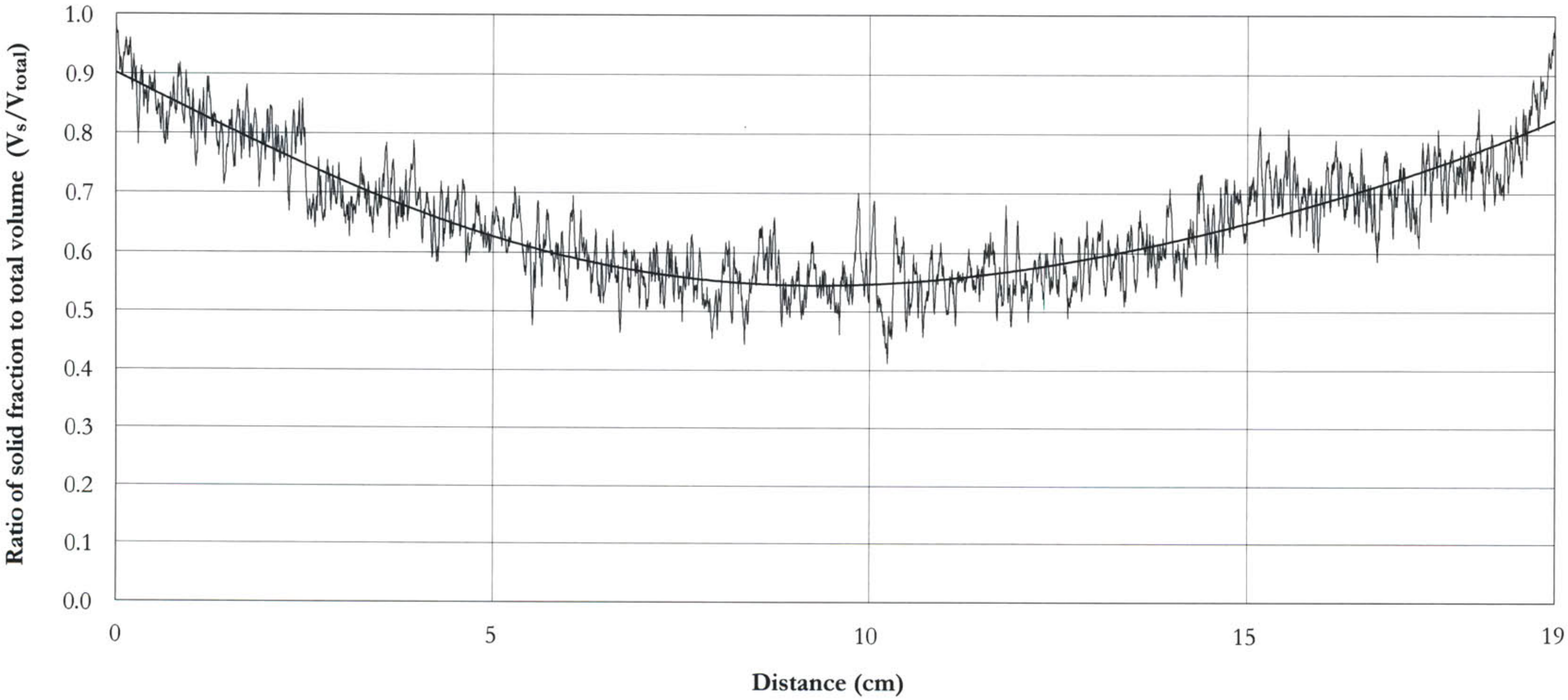


Figure 5.4.19
Image of second gypsum beam prototype
cast with a fabric liner



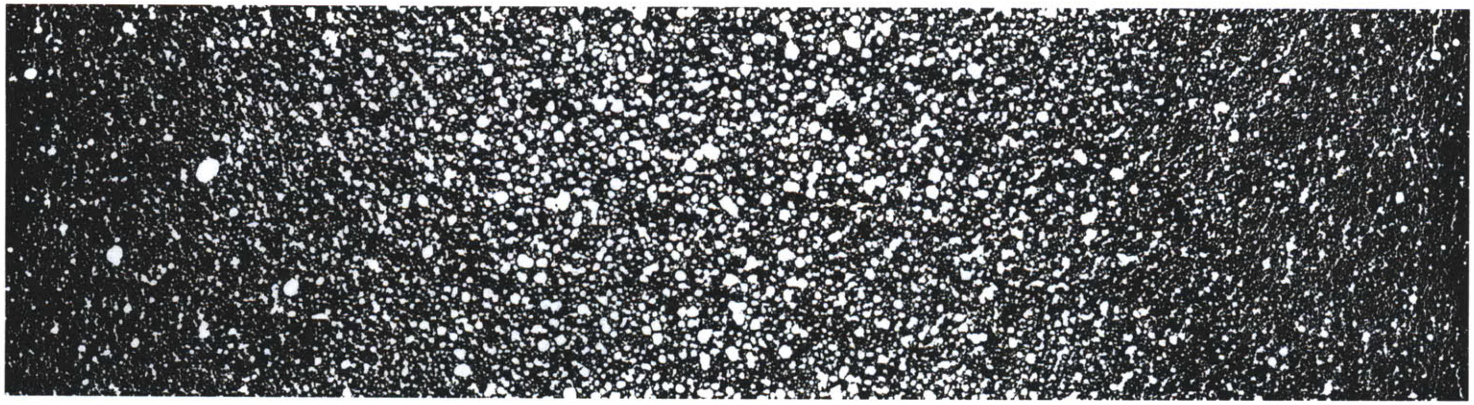


Figure 5.4.20
Image analysis of second gypsum beam prototype cast with a fabric liner

5.5
Strength and Thermal Testing

Table 5.5.1
Constituent proportions used to produce aerated cylinders for compression testing (Specimens C1, C2, C3, D1, D2, D3)

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	10,000	61
Type I/ II Portland Cement	5,000	31
Quicklime	1,310	8
Aluminum Paste	23	0.14
Total Dry Constituents	**16,333**	
Water	**8,160**	

Table 5.5.2
Constituent proportions used to produce non-aerated cylinders for compression testing (Specimens B1, B2, B3)

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	4,000	62
Type I/ II Portland Cement	2,000	31
Quicklime	480	7
Aluminum Paste	0	0.00
Total Dry Constituents	**6,480**	
Water	**3,240**	

Compression testing

In an effort to establish some basic strength metrics for the non-autoclaved aerated concrete I worked with during my hands-on experimental investigations, I conducted a series of compression tests of specimens of different densities. All of these tests followed ASTM C39/C39M – *11 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. Because some of the tested specimens fell close to the lower density limit of 800 kg/m^3 permitted with this ASTM testing standard, these results are only provided for reference.

I tested three different mix designs that approximately represented the spectrum of densities found in the castings I had been producing up until this point. I wanted to test three densities so that I could begin to understand the range of strengths I could expect to find in the gradient density castings I had been producing. The first set of specimens was made using the same standard mix design I used for most of my casting experiments (Table 5.5.1), from the columnar gravity tests to the final beam prototype castings. These aerated specimens represented the lowest density regions I was casting in my gradient density experiments (around 700 – 800 kg/m^3). The second series represented an intermediate density. These specimens were cast from the same mix design as the first set (Table 5.5.1), but these specimens were agitated during aeration to collapse the air-void matrix as it formed and produce a higher density matrix that might be similar to the higher densities I was able to achieve through my various densification strategies (900 – 1200 kg/m^3). The third set of specimens was cast without aluminum, thus producing a full density cement lacking of any macro air-voids due to chemical aeration. Table 5.5.2 gives the mix design for these non-aerated specimens.

Table 5.5.3 gives the results from these compression tests. All cylinders were 4 inches in diameter and 8 inches in height. They were cast and allowed to moist cure for 21 days. Prior to testing, the cylinders were allowed to air dry for one week. For each of the

Specimen Designation Number	Density (kg/m³)	28-day Compressive Strength (MPa)	Ave 28-day Compressive Strength (MPa)
B1	1385*	10.50	10.41
B2	1385*	10.51	
B3	1385*	10.21	
C1	1087**	2.36	2.63
C2	1087**	3.06	
C3	1087**	2.47	
D1	807**	1.61	1.60
D2	807**	1.60	
D3	807**	1.59	

*Room-dry density after 100 days

**Room-dry density after 78 days

Table 5.5.3
Compression testing data

three densities tested, three cylinders were produced and tested in uniaxial compression on a 100,000 lb-capacity Instron machine (Plate 53-55). For the non-aerated specimens, a constant loading rate of 120 kN/min was applied for specimen B1. This proved too rapid a loading rate for obtaining a sufficient number of data points, so specimen B2 and B3 were loaded at a rate of 60 kN/min. Because the aerated cylinders (C1, C2, C3, D1, D2, D3) were relatively weak compared to the full-density specimens, they were instead tested using a controlled displacement method. The rate of displacement was 0.5mm/min. A plot showing compressive strength versus density (Fig. 5.5.1) shows that strength decreases as density decreases, as one would expect. As can be seen in Figure 5.5.2, the values obtained from these compression tests verify that the material I am producing has consistent compressive strengths with those reported for non-autoclaved aerated concretes (Valore 1954, 820).

Three point bending test

In addition to compression testing, I also conducted a three-point bending test on the final gradient density beam prototype that I cast using the fabric-lined gypsum design. This test was conducted to shed light on

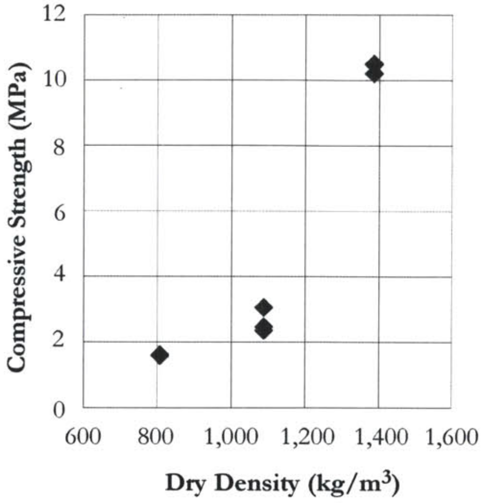


Figure 5.5.1
Compressive strength versus density

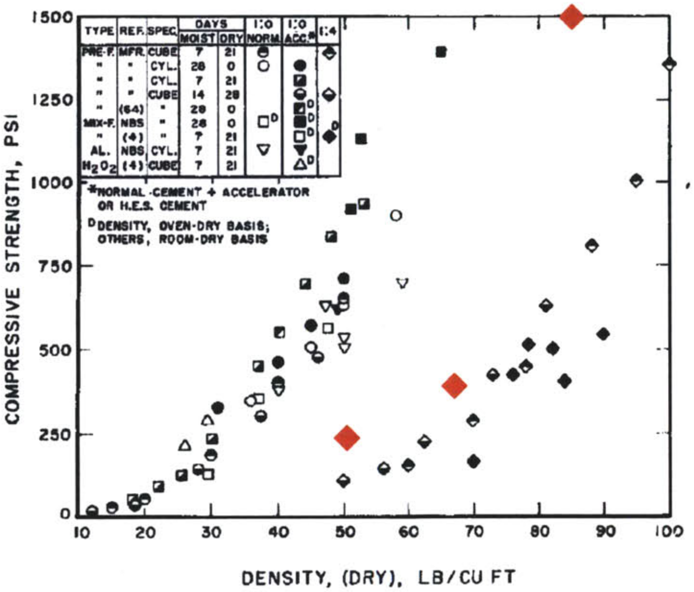


Figure 5.5.2
Compressive strength versus density of moist-cured cellular neat cement and 1:4 cement sand mixtures (reproduced from Valore 1954, 820) with values I obtained overlaid in red.

the basic behavior of the material in bending. It also gave a value for the modulus of rupture for the gradient density beam. The beam prototype was tested on a 3-point loading frame.

The three-point-beam test was conceived first to establish the failure mechanism for the variable density beam design that is depicted in Figure 5.4.16. Due to the relative weakness of aerated concrete, I wanted to determine if crushing due to shear of the weak, low-density cellular material distributed along the neutral axis could occur. I was also interested in the possibility of delamination between the different density regions in the beam. In the end, because the beam was not designed with tensile reinforcing, these potential mechanisms for failure could not be tested. Because brittle ceramic materials are generally much weaker in tension than compression, reinforcing must be introduced in some manner before a complex failure mode such as shear crushing or delamination might occur. As reported by Narayanan and Ramamurthy (2000), direct tensile to compressive strength ratios for AAC has been reported to be anywhere from 0.10 to 0.35. Despite the variation in density I was able to achieve in the beam prototype tested, the overall behavior in bending was the same as would be expected of a homogeneous unreinforced beam. This behavior is characterized by brittle fracture, initiated at the mid-point on the bottom face of the beam where the tensile forces are the greatest (Figure 5.5.3).

Based on the three-point bending test of this beam, it is obvious that tensile stresses on the lower extreme fibers of the beam caused failure before any other mechanisms could present themselves. Further experiments that include tensile reinforcing along the bottom of the beam in conjunction with the density gradient profile already produced would be necessary for the possibility of these other types of failure modes to occur. It is clear, based on the bending test conducted on this beam, that shear failure and delamination can be ruled out for any beam of this configuration that does not have tensile reinforcing.

Figure 5.5.3
Beam prototype after 3-point bending test. Brittle fracture failure mode apparent.

To calculate the modulus of rupture for the beam, the following formula was used:

$R = 3\,PL/2bd^2$

where:
R = modulus of rupture [*MPa*]
P = maximum applied load indicated by the testing machine [*N*]
L = span length [*mm*]
b = average width of specimen, at the fracture [*mm*]
d = average depth of specimen, at the fracture [*mm*]

The dimensions of the beam are given in Table 5.5.4. The maximum applied load was 5040 N. Based on the beam's loading capacity and the dimensions of the beam, the modulus of rupture obtained from the bending test is 0.781 MPa. Based on one's understanding of the distribution of internal forces in a beam under three-point bending (Figure 5.4.13), we can assume that this modulus of rupture is associated with the material properties of the material located on the tension face of the beam, having a density of 1,190 kg/m^3, as stated in the previous section. This is corroborated by the fact that the ratio of flexural strength to compressive strength, as reported by Narayanan and Ramamurthy (2000, 326), has been shown experimentally to be between 0.22 and 0.27. This would mean that if the flexural strength of the beam was determined by the highest density material in the beam (1,190 kg/ m^3) on

Table 5.5.4
Dimensions for beam prototype cast in fabric-lined gypsum mold

Beam Dimensions	(inches)
Gross Length	26
Gross Width	6
Gross Height	7.5
Support Span	22.5

the botton face of the beam, and that based on the density of 1,190 kg/m^3 we can estimate a compressive strength of around 3 MPa (based on the compression data shown in Figure 5.5.1) then the modulus of rupture should be somewhere in the range of 0.66 – 0.81 MPa. In fact, the experimentally obtained modulus of rupture, 0.781 MPa, falls right in the middle of this range. Using the same relationship between compressive strength and flexural strength, the modulus of rupture for the material found at the centerline of the beam should be between 0.33 – 0.405 MPa, a significantly lower value. By weighing the whole beam, an aggregate density of 853 kg/m^3 was measured. This means that by introducing this gradient density into the beam, one is able to achieve a material reduction of 337.39 kg/m^3 over a beam of uniform density of 1,190 kg/m^3, which equates to a 28 percent reduction in material usage while maintaining the same flexural strength of a beam with a uniform density of 1,190 kg/m^3.

Because the determination of tensile and flexural strength is more sensitive to the conditions of the test than that of compressive strength, multiple beams would need to be produced and tested for these calculations to be more meaningful. Additional testing would allow one to establish this relationship more confidently and compute improved strength-to-weight ratios achieved by strategically distributing density within any prismatic flexural member.

Future experiments that include testing of a uniformly foamed cellular beam and a uniformly full density beam, along with additional gradient density beams, would allow one to establish more accurate predictions for the material savings one could achieve through the intelligent distribution of densities within a beam of this design. Regardless, this initial calculation starts to give a rough idea of the magnitude of material savings one could start to achieve through the deployment of density gradients in structural members designed for flexure.

Thermal test

A thermal test was run at the Fraunhofer Center for Sustainable Energy Systems located in Cambridge, MA. A block was tested of dimensions 11.5 in. x 11.5 in. x 3 in. cast out of the same standard mix design used for the majority of the experimental work. The specimen had been moist cured for 28 days and then oven dried until it had a nominal moisture content between 1-5%. The dry density of the block was 761 kg/m^3. Nitin Shukla, a member of the technical staff at the Fraunhofer center ran a steady-state heat flow test using a LaserComp FOX 305 heat flow meter (Figure 5.5.4). The test ran for approximately 5 hours with a temperature delta of 25 °C, with T upper held at 40 °C and T lower at 65 °C. This test resulted in a thermal conductance value of 0.1611 W/m-K.

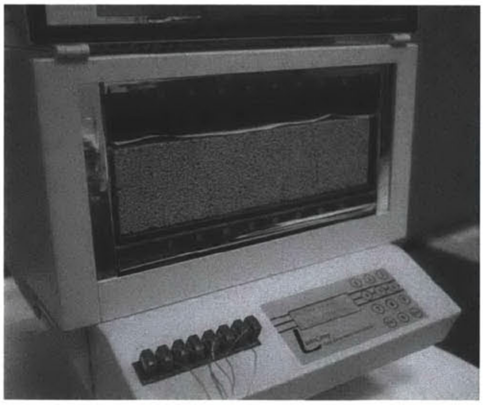


Figure 5.5.4
Steady state thermal testing setup using a LaserComp FOX 305 heat flow meter at the Fraunhofer Center for Sustainable Energy Systems, Cambridge, MA.

Tada (1986) proposed the following model, based on empirical testing data, for the thermal conductivity of aerated concrete as a function of bulk density:

$$k = (2.43 \times 10^{-4})\rho + (4.62 \times 10^{-3})$$

where k = thermal conductivity of aerated concrete in W/m-K; and ρ = density of aerated concrete in kg/m^3. This model is valid for material having a moisture content between 1.6% and 5.0% by volume. The experimental thermal conductance value of 0.1611 W/m-K I obtained from the above-mentioned steady-state heat flow test is predicted by Tada's model with a fair degree of accuracy, with the experimentally obtained value of 0.1611 W/m-K being 0.028 W/m-K lower than the 0.189543 W/m-K predicted by the model. By comparing my results to this model, one can be fairly confident that this thermal conductance value is an accurate representation of the k-value for the fully aerated material found in the test specimens I produced throughout my investigations into creating variable density aerated concrete.

Table 5.5.5 lists the thermal conductance values for some common building insulation types as well as normal density concrete and wood. The thermal conductance of the fully aerated concrete found in the specimens I have produced is substantially higher than

Material	Thermal Conductance	
Mineral insulation:	0.04	W/m-K
Fiberglass insulation:	0.045	W/m-K
Polyisocyanurate foam:	0.020	W/m-K
Concrete:	0.8-1.28	W/m-K
Wood (oak):	0.150	W/m-K

Table 5.5.5
Thermal conductance values for common building insulation types and building materials (Gibson and Ashby 1997).

what one would expect for a typical insulation material, but is much lower than that of non-aerated structural concrete. In fact, its conductance is similar to that of solid wood, which typically has a *k*-value of around 0.150 W/m-K [kiln dried oak].

Chapter 6: Conclusions

In this chapter I review this thesis' contributions within the field of building materials research. In addition, I present potential applications and extensions of the initial variable density casting methods developed. Ongoing and future experimental work is also discussed.

In the most general sense, this work is concerned with the development of variable density concrete. There are two fundamental motivations for this work. First, as described in Chapter 3, there is an immediate and real need for creating better concrete products for the construction industry. The ability to produce precast concrete building components that incorporate variations in internal composition have immediate application within existing production models. By being able to vary the internal material properties of a precast element, one can create more resource and energy efficient building products. These new precast elements have the potential to easily replace existing systems widely in use today. The precast elements that this thesis proposes are shown in Figure 5.4.12. As a direct outgrowth of the casting techniques I have described in Chapter 5, this table of elements have the potential to be easily produced based on a modified precast aerated concrete production model. Blocks, beams, columns and panelized systems are the most obvious application for this type of material. Essentially, these elements would be a hybrid of lightweight aerated concrete filling the majority of the interior volume of an element, with the surface regions of the component containing dense and hard concrete.

The second broad motivation for the work has been to think more speculatively about the implications of being able to control the internal distribution of material within a monolithic substance. Though not immediately realizable, the concept of being able to cast a single material that can integrate all of the performance requirements for a building is an exciting conceptual proposition. Mainly as a thought experiment, I am interested in speculating about alternative ways of conceiving of architecture, not as something that is constructed in the sense of assembling and building-up, as is the tradition in modern architecture and construction, but as something that is generated or manipulated into being. One could borrow from some of the terminology used for the processing for materials such as "to influence" or "to work." These terms imply not just the "creation of a thing," but the alteration of an already existing thing.

This second, more speculative, strain within the work follows a theoretical bent but is also concerned with thinking about possible future methods for creating buildings. For example, what if one could cast an entire house using one variable property material? At a simple and somewhat abstract level, one could imagine prototypical wall, floor and roof sections and what these elements might look like if one was able to dictate material properties in a single monolithic member/skin/barrier instead of having to assemble materials.

Tensile reinforcing

Though I have not explored tensile reinforcing as part of this project, being able to create dense regions in a lightweight precast element means that the inclusion of reinforcing in those dense regions would be advantageous. Throughout this work, the idea has been that overlaying a design for tensile reinforcing on top of this way of organizing a cementitious material would be the most logical next step in the design and development process. Throughout the work I was interested in conducting experiments with tensile reinforcing but ultimately decided to focus my attention on the development of casting gradient densities. I wanted to develop the gradient density casting methods to a proof-of-concept level before beginning to investigate reinforcing systems.

There are two paths forward for investigating tensile reinforcing within a variable density typology.

First, by including the same bar or wire reinforcement found in typical reinforced concrete, one would be able to design structural members that were in many ways similar to traditional normal weight members. If reinforcing steel is located in the densified regions of a beam, for example, then the common issues of low bonding strengths found in reinforced aerated concretes could be mitigated. In essence, the dense regions of any gradient density morphology are ideally suited for tensile reinforcing. The second possible mode of tensile reinforcement could be through the inclusion of high strength fibers. Fiber reinforcing has been used in aerated concretes (especially NAAC) in an effort to increase tensile strengths and mitigate shrinkage cracking. By including fiber reinforcing within a gradient morphology, the stability and strength of this material could be increased as well.

Ongoing work: cellular matrix agitation tests

The fundamental ambition underlying all of my experimental work looking at the interaction between molding materials the material being molded, is the idea that it is desirable to be able to create a basic inverse relationship between density and the distance from the surface of a cast geometry. This general relationship between location within a volume and the density at that location is illustrated in Figure 6.1.1. Based on experimental results, up until about 6 inches into a cast, this relationship can be generally approximated with the simple equation: *[$\rho = -150d + 1500$]*, where *(d)* is the distance from the surface in inches and *(ρ)* is the density in kg/m^3.

But what if one wanted to be able to densify regions on the interior of a volume? Current hands-on experimental work has been focused on answering this question and coming up with ways to produce interior densification. It is easy to see the desirability of having an inverse relationship between density and distance from a surface (durability, toughness, moment of inertia, etc.), but there are also reasons why one might want to introduce stronger material on the interior of a variable density concrete element. Simply put, interior densification would provide additional flexibility when

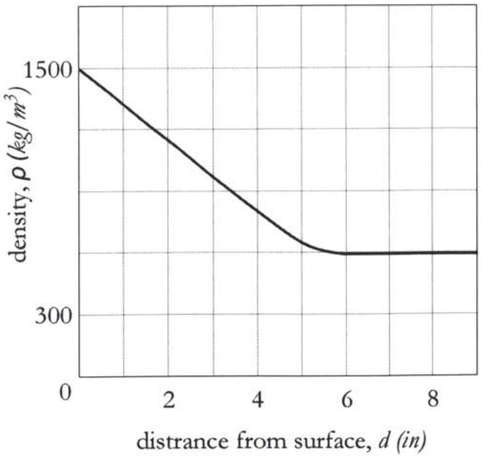


Figure 6.1.1
Relationship between proximity to the surface of a cast and density

designing variable density components, for example allowing one to locate denser (and thus stronger) material in diagonal planes oriented along lines of internal shear force found in beams or allowing one to create an internal space frame within a monolithic geometry.

On first thought, one could theoretically introduce absorptive materials to the interior of casts, drawing water out of the aerating concrete and producing densification, but it quickly becomes clear that the challenges associated with this would potentially be prohibitive. If one introduced a material such as gypsum, then one would have non-structural material embedded precisely at a location where one is trying to provide the greatest strength.

I imagined two possible ways to try to create internal densification: first, engineer structural elements (here the best candidate would be tension reinforcing) into the aerating slurry that would have absorptive properties. This would cause the concrete matrix to densify around these theoretical structural elements; second, disturb the cellular matrix during or immediately following aeration, causing local collapse and consolidation. This disturbance could potentially be introduced through the insertion of a rod or mat vibrating at high frequencies.

I am currently investigating the agitation of the fresh cellular matrix in an attempt to understand if this second method for densification is viable. I know from experience working with foaming cement slurries that they are unstable during aeration and for the two hours after the initiation of aeration before the mixture had fully set. If one even touches the surface of an aerated mixture during aeration or in the few hours after, it tends to collapse and solidify where it has disturbed. Based on this observation, the idea is that if one could disturb an isolated region of the matrix, collapse and densification could be achieved in that region. I wanted to know when the ideal time would be for this matrix disturbance. To understand this, I cast three cylinders with 3/8" metal threaded rods suspended vertically in the matrix as it aerated. The slurries were allowed to aerate and expand for different lengths of time before the rods were removed. The hope was that removal of the rods would disturb the matrix and cause collapse. By analyzing the resulting cross-sectional composition

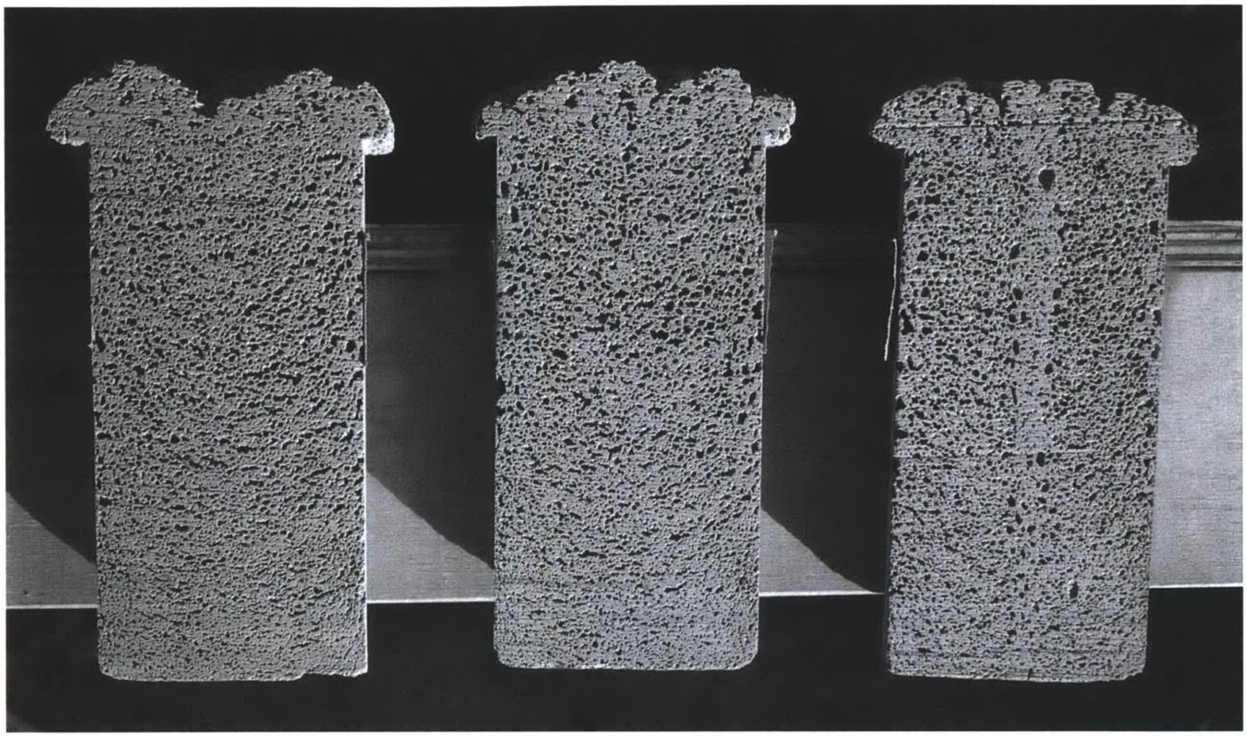

a. b. c.

Figure 6.1.2
Matrix agitation tests.
a. Threaded rod removed after 30 minutes
b. Threaded rod removed after 45 minutes
c. Threaded rod removed after 60 minutes

of the aerated cylinders, one could identify the timing that had the greatest densification effect on the forming matrix. The rods were removed 30, 45, and 60 minutes after initial mixing of the wet and dry constituents. As can be seen in Figure 6.1.2, the disturbance caused by the removal of the threaded rod had little effect on the cellular structure at 30 and 45 minutes. Only the removal of the rod at 60 minutes had any noticeable effect. In this specimen, there is a distinct vertical region of denser material along the centerline of the cylinder where the rod had been located. In addition, by looking at the top of the cylinders, one can see that the cylinder agitated after 60 minutes expanded the least out of the three. I concluded that by disturbing the matrix after substantial aeration had completed, collapse could be sustained. It appears that any collapse induced during aeration (which was the case for the 30 and 45 minute removal times) is reversed by continued aeration after the disturbance.

These tests are only the first step in investigating the potential for causing internal densification through mechanical disturbance of the cellular matrix. Further experimentation would need to be conducted in order to come to any conclusions about this method. High frequency vibration is the next logical step. Vibration of fresh concrete has been the most common method for consolidation and densification of traditional concrete for decades. It follows that vibration of aerated concrete could be deployed to cause densification. It is currently not know if the use of high frequency vibration could be used to cause isolated densification or if the vibration would propagate through any casting and cause uniform collapse throughout. Further tests using a commercially available concrete wand vibrator suspended in an fresh aerated mix would be able to determine any potential for this line of inquiry.

Future Work

As I have described, the continuation of this work could follow a few paths. The incorporation of tensile reinforcing must certainly be investigated along with the continued development and refinement of the casting techniques. What I have been able to accomplish for this thesis really only constitutes the beginning of a potentially rich ongoing research program. I have only begun to scratch the surface and produce experimental results that essentially provide a proof-of-concept for a gradient density material. To further improve the material and produce wider ranges in density, better and stronger absorptive casting materials must be investigated. In addition, there is much opportunity for the further development of permeable barriers integrated with absorptive substrates.

The major issues that must be addressed in future work include the drying shrinkage associated with NAAC and the instability it produces in the material. The negative interactions between absorptive molding materials and the hydrating concrete must also be addressed. My initial test that included a fabric barrier between the gypsum mold and the slurry provide promising indications that a combination of a permeable barrier and an absorptive substrate has the greatest potential for creating the ideal conditions for densifying chemically aerated concrete.

Beyond the general improvement of densification methods, the development of hybrid permeable and absorptive molding technologies tailored to vary the removal of water over the surface area of a formwork would open up the possibility for vastly increasing the complexity and sophistication of internal material distribution. For example, by changing the level of permeability/absorptivity along the length of a beam, the distribution of material in the beam could be controlled not only through its cross section as I achieved in the beam prototypes discussed in Chapter 6, but along the length of the beam as well. This would allow one to imagine highly reticulated three-dimensional material distribution regimes.

Work into gradient density columns is also an area for future development. Spun columns would most likely have to be oriented horizontally to facilitate spinning and avoid densification due to gravitationally induced hydrostatic pressure. But by spinning in a horizontal configuration, potential issues related to gravity and slurry expansion could interfere with proper aeration and the introduction of uniform radial gradients. The challenges associated with spinning columns to achieve gradient densities are potentially prohibitive, but merit further investigation.

Summary of contributions

The experimental work completed for this thesis has shown that there are a number of simple casting methods that are effective at producing density gradients in chemically aerated concrete. The most promising technique combines the use of an absorptive formwork with a permeable barrier/liner. These techniques have the potential to be deployed in beam, column, block and panelized morphologies (Figure 5.4.12).

Tensile reinforcing was not investigated as a part of this research, but bar, wire or fiber reinforcing all have the potential to be incorporated into these gradient density precast components.

These methods for producing density gradients in aerated concrete have only been tested within a specific range of scales that are relevant to applications as structural building components (Figure 5.4.9). Further work would need to be conducted to develop casting methodologies for producing gradients at substantially larger of smaller scales (e.g., at the furniture scale or whole building scale.)

The goal of this project was to imagine a more sophisticated concrete. This research has shown that variable density concrete has the potential to achieve higher strength-to-weight ratios, thus reducing the amount of material needed for a given function. As well, by cellularizing concrete, one can introduce beneficial thermal properties. When combined with the utilization of room temperature curing and low embodied energy Portland cement replacements such as Fly ash, one can imagine a concrete that has the potential to vastly improve on existing technology.

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Appendix A
Plates

Plate 1
Early casting setup

Plate 2
First gravity test column partially demolded

Plate 3
First columnar specimen cut open; higher density material is apparent at the lower bound of the cast.

Plate 4
Columnar sample tbalanced to determine its center of mass.

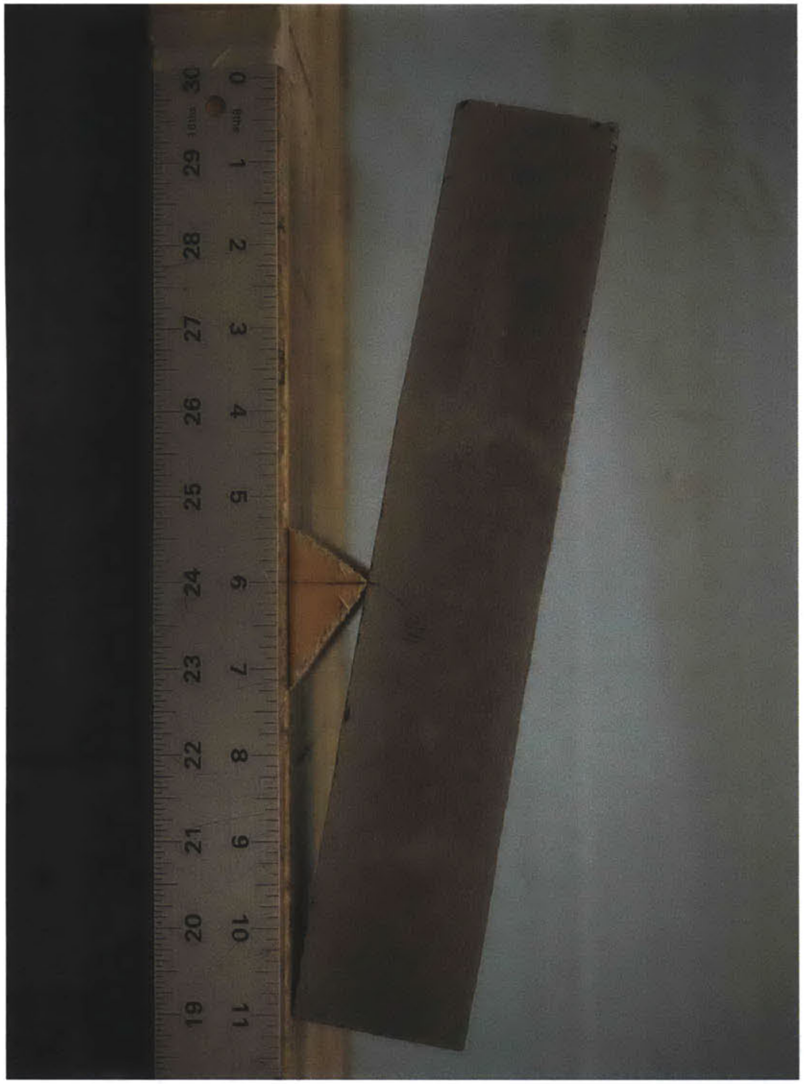

Plate 5
First centrifuge mold

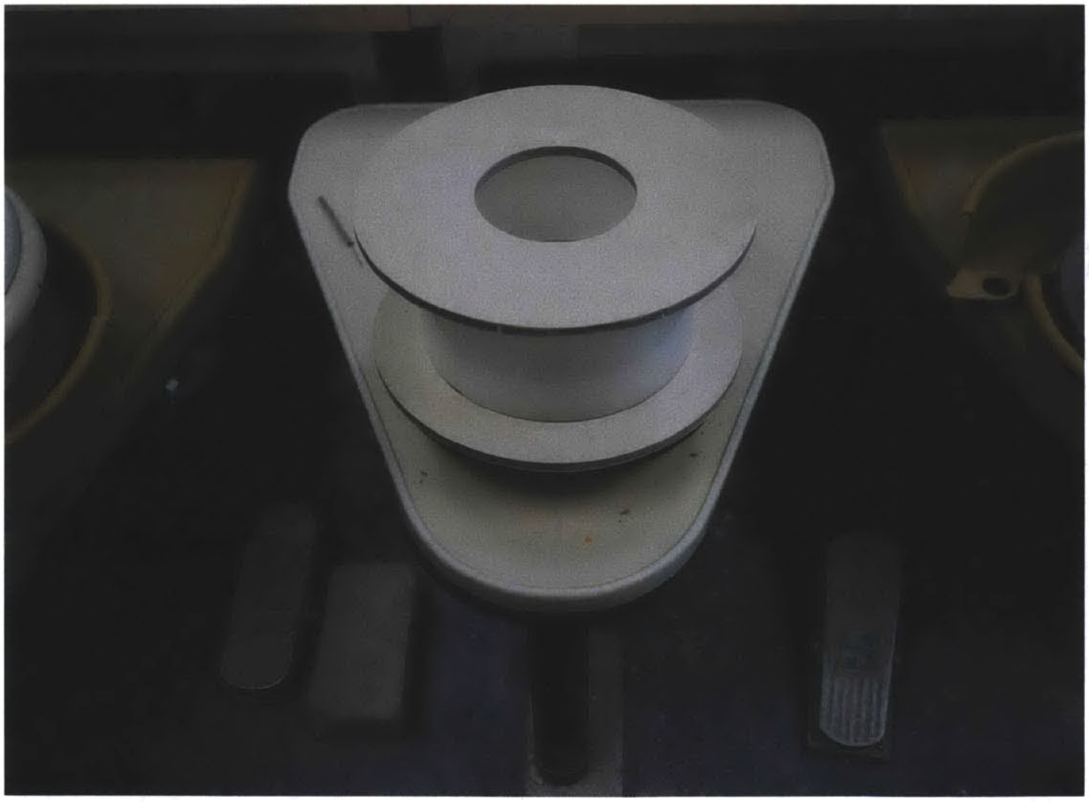

Plate 6
First centrifuge mold

Plate 7
Centrifuge mold in motion

Plate 8
First centrifuged specimen

Plate 9
First centrifuged specimen

Plate 10
Second centrifuged specimen

Plate 11
Second centrifuged specimen

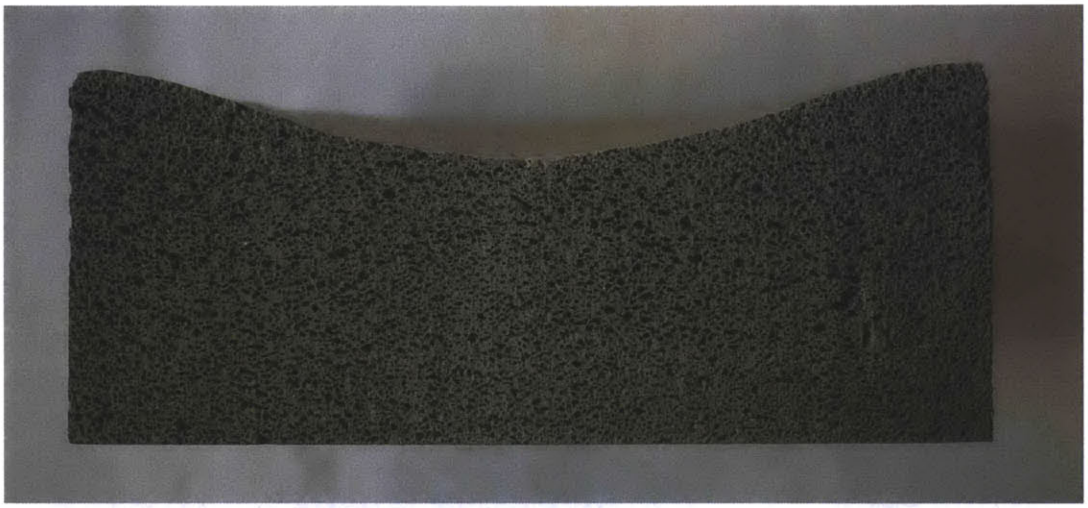

Plate 12
Cross section of first centrifuged specimen

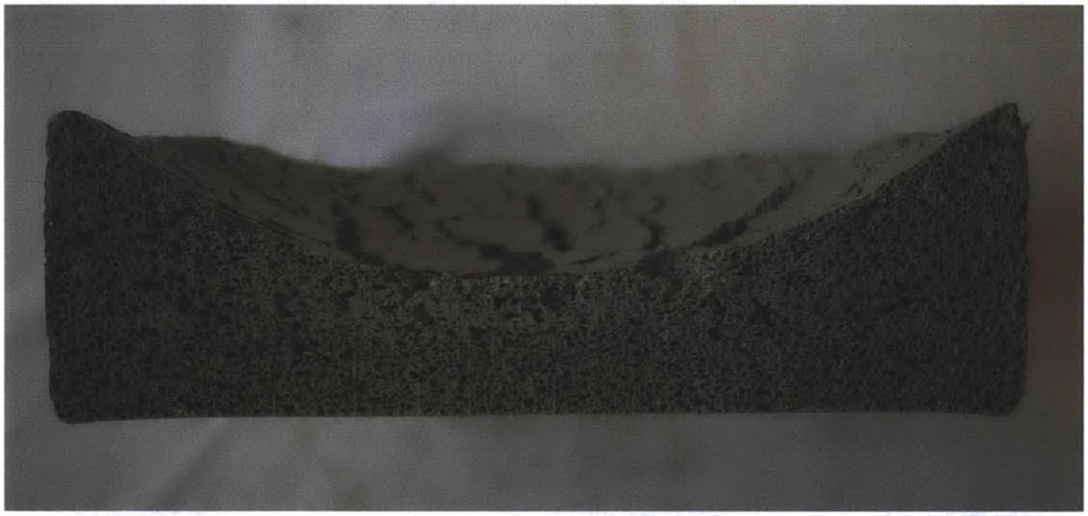

Plate 13
Cross section of second centrifuged specimen

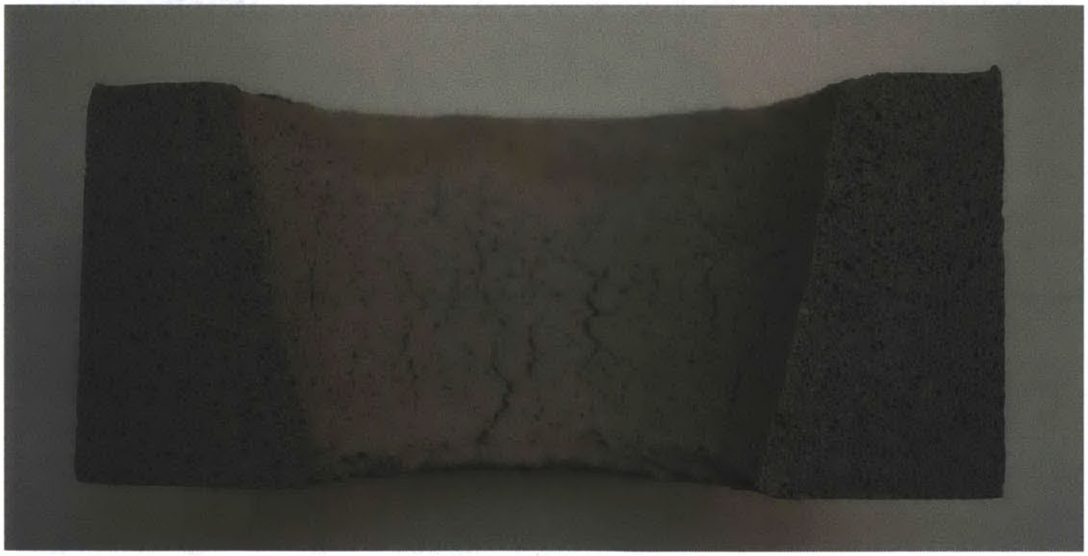

Plate 14
Cross section of third centrifuged specimen

Plate 15
Fabric molds under construction

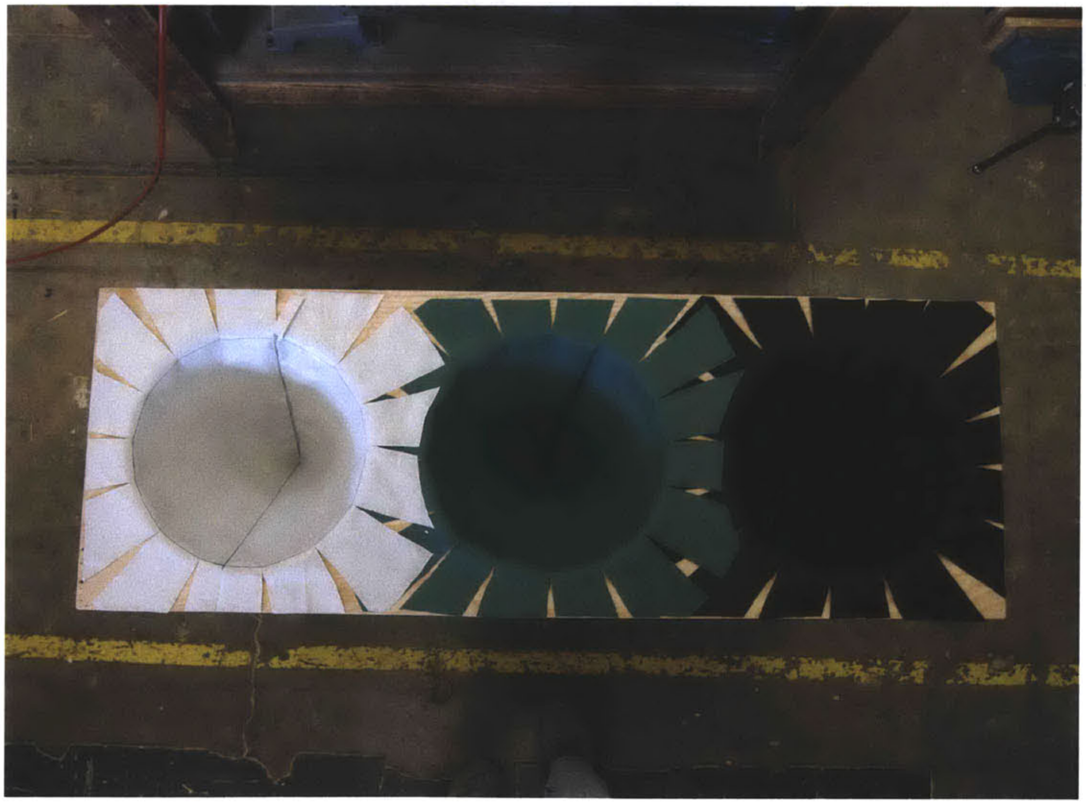

Plate 16
Fabric molds under construction

Plate 17
First round of casting in fabric molds

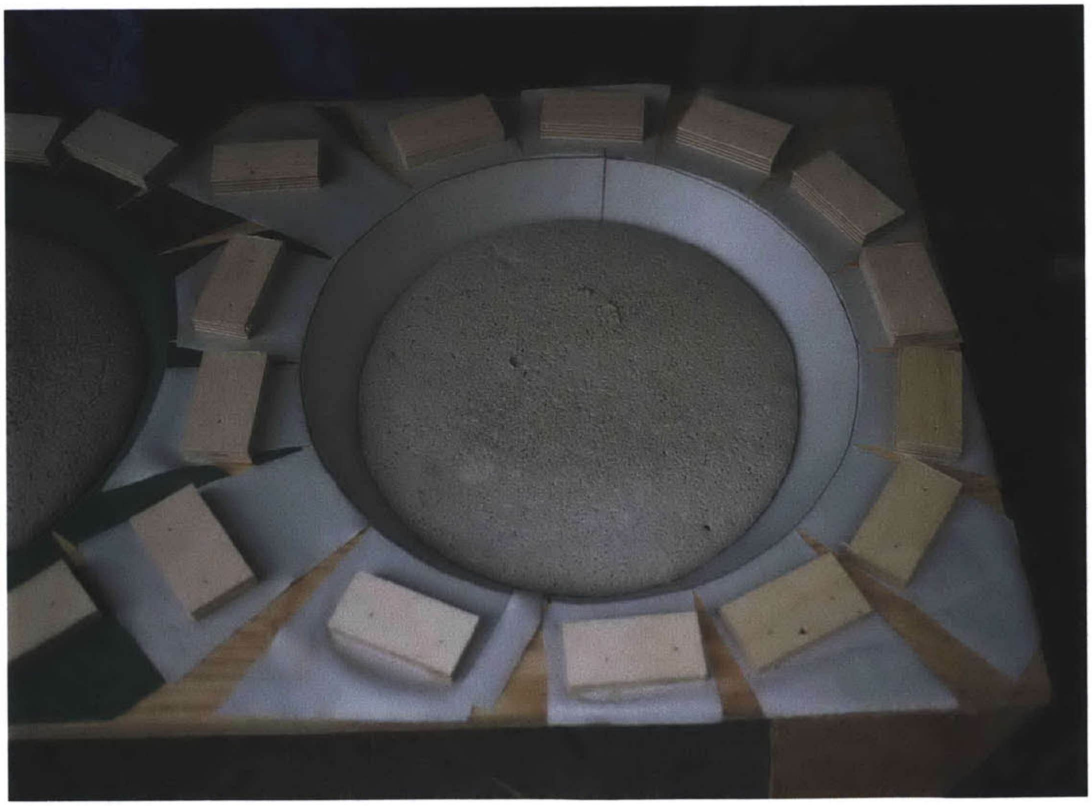

Plate 18
First round of casting in fabric molds

Plate 20
Fabric-formed conical specimen after demolding

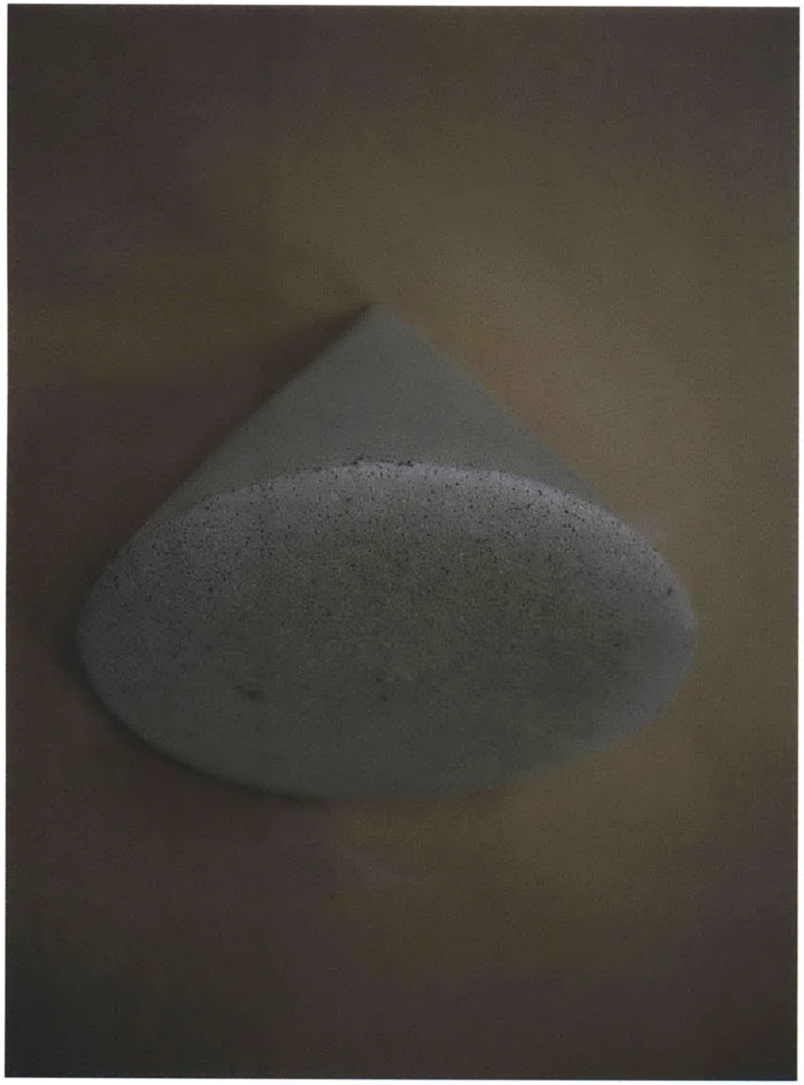

Plate 19
Fabric-formed conical specimens after demolding

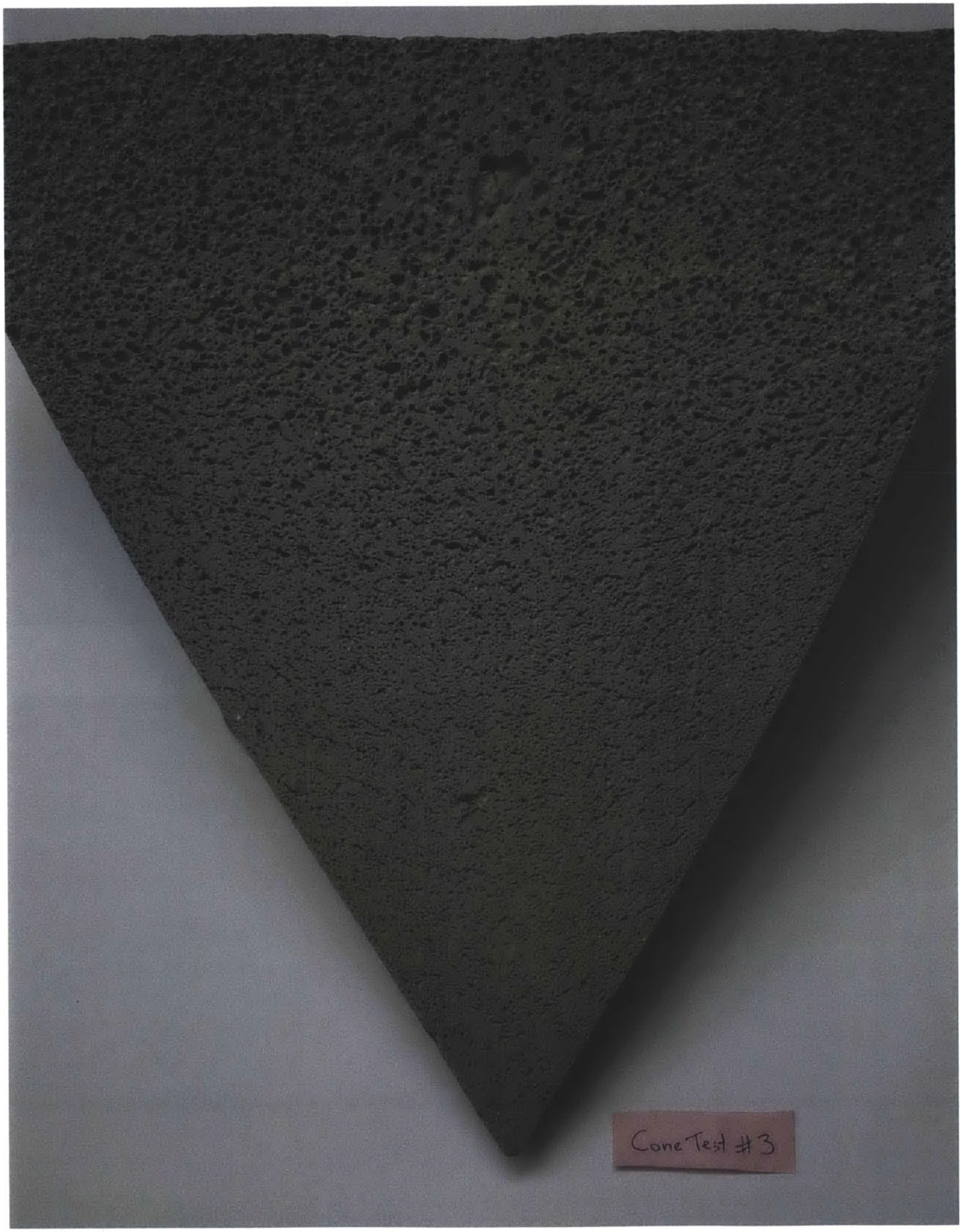

Plate 21
Internal cellular composition of fabric-formed conical specimen #3

Plate 22
Internal cellular composition of fabric-formed conical specimen #4

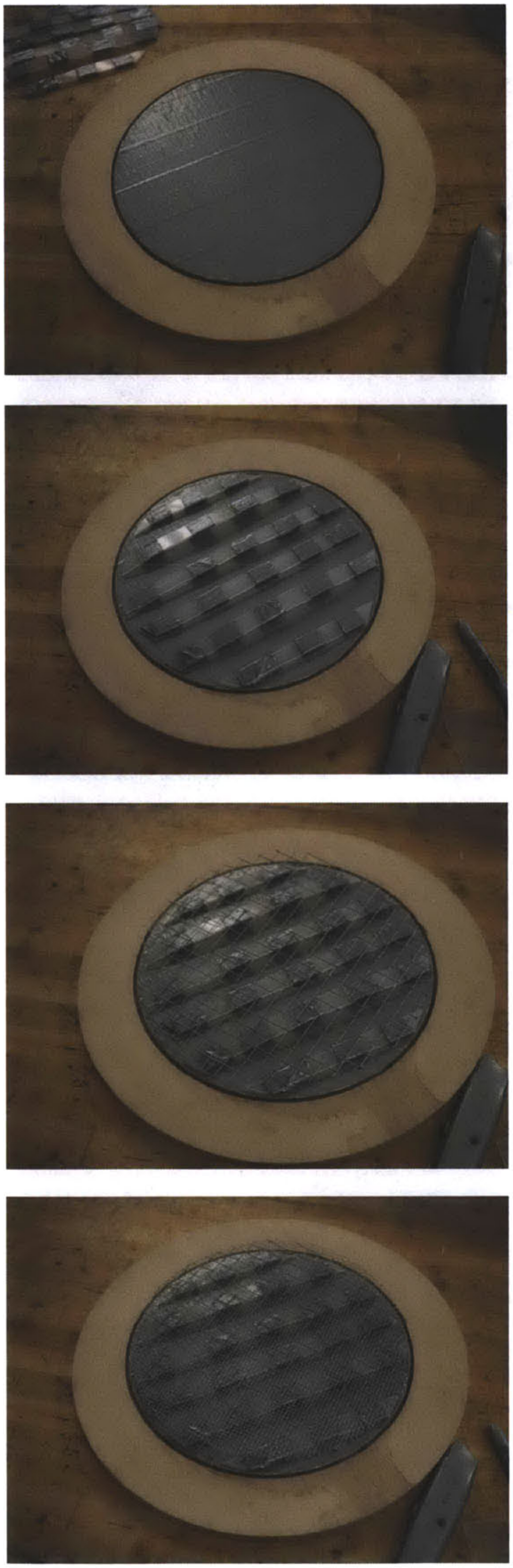

Plate 23
Drainage mat components for base of fabric-lined centrifugal mold

Plate 25
Centrifuged specimen prior to fabric sleeve removal

Plate 24
Drainage mat prepared for fabric sleeve

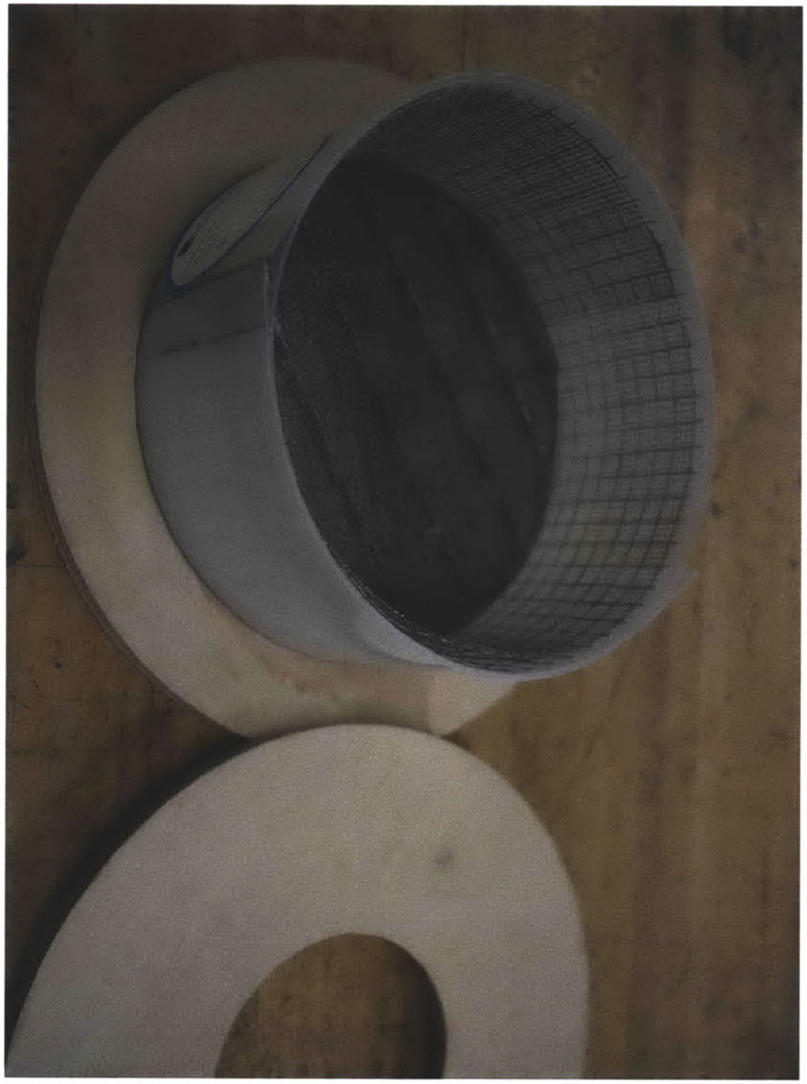

Plate 26
Wire cage and fabric sleeve after demolding

Plate 27
Demolded fabric-formed cylinder showing
the impressions left by the fabric

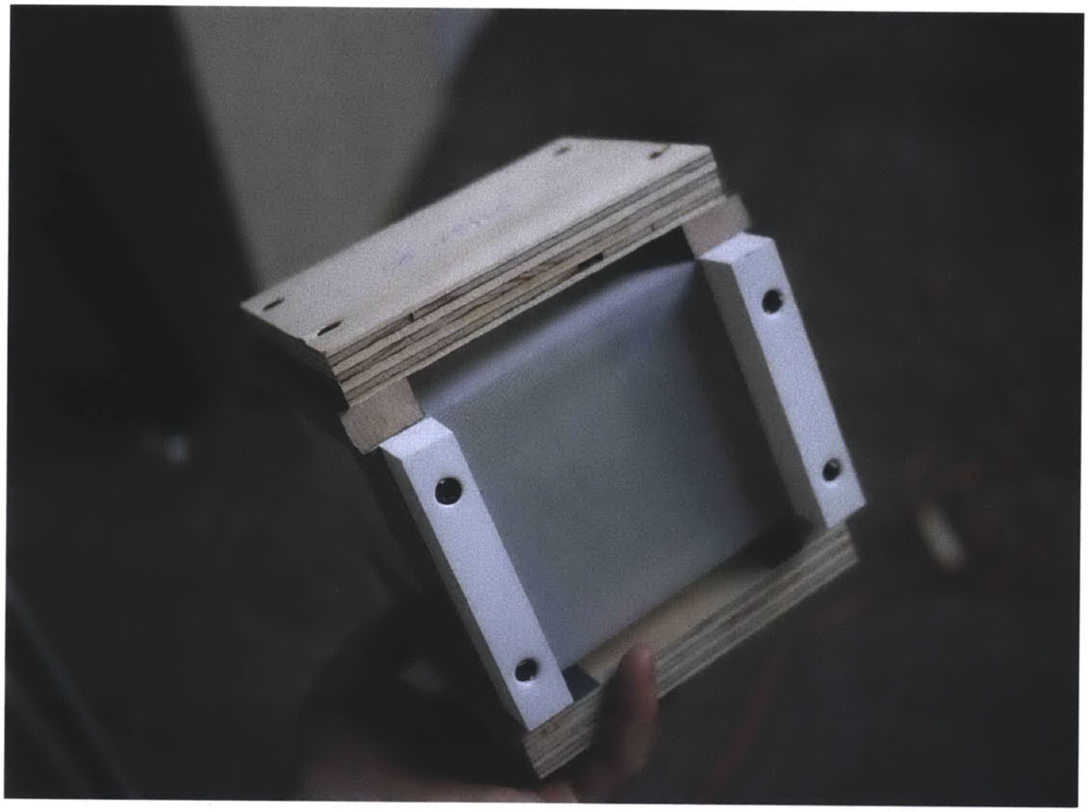

Plate 28
Three-sided mesh mold

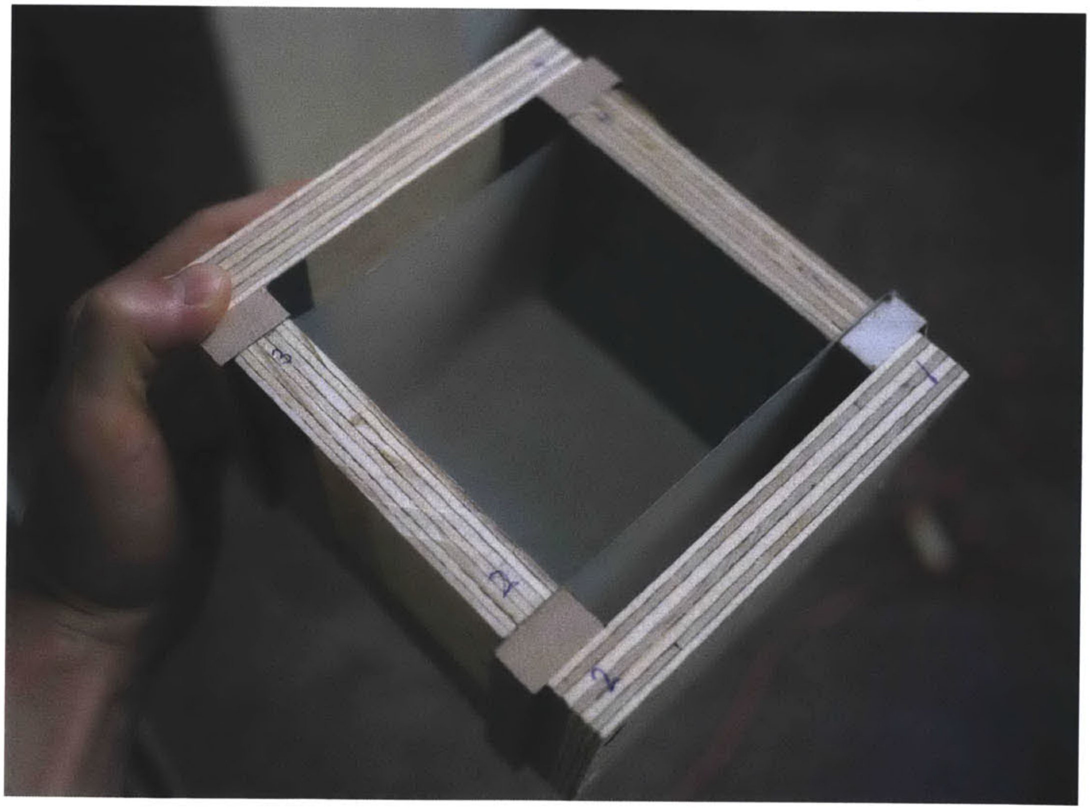

Plate 29
Three-sided mesh mold

Plate 30-34
Casting in meshes with mesh openings varying from 105 μm to 210 μm.

Plate 36
Super absorbent polymer crystals partially cleared from the surface of a cast specimen. Chalky surface produced by unhydrated cement is visible.

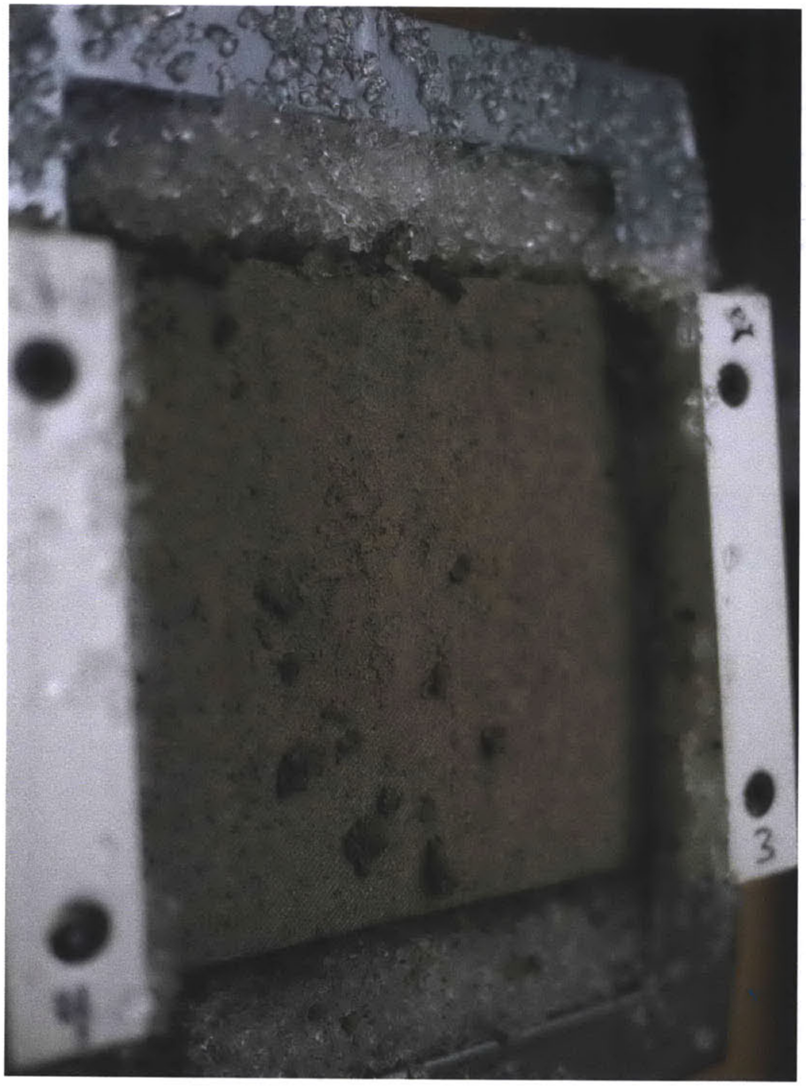

Plate 35
Mesh mold with super absorbent polymers packed against mesh filter

Plate 37
Partially demolded aerated concrete specimen cast in super absorbent polymers

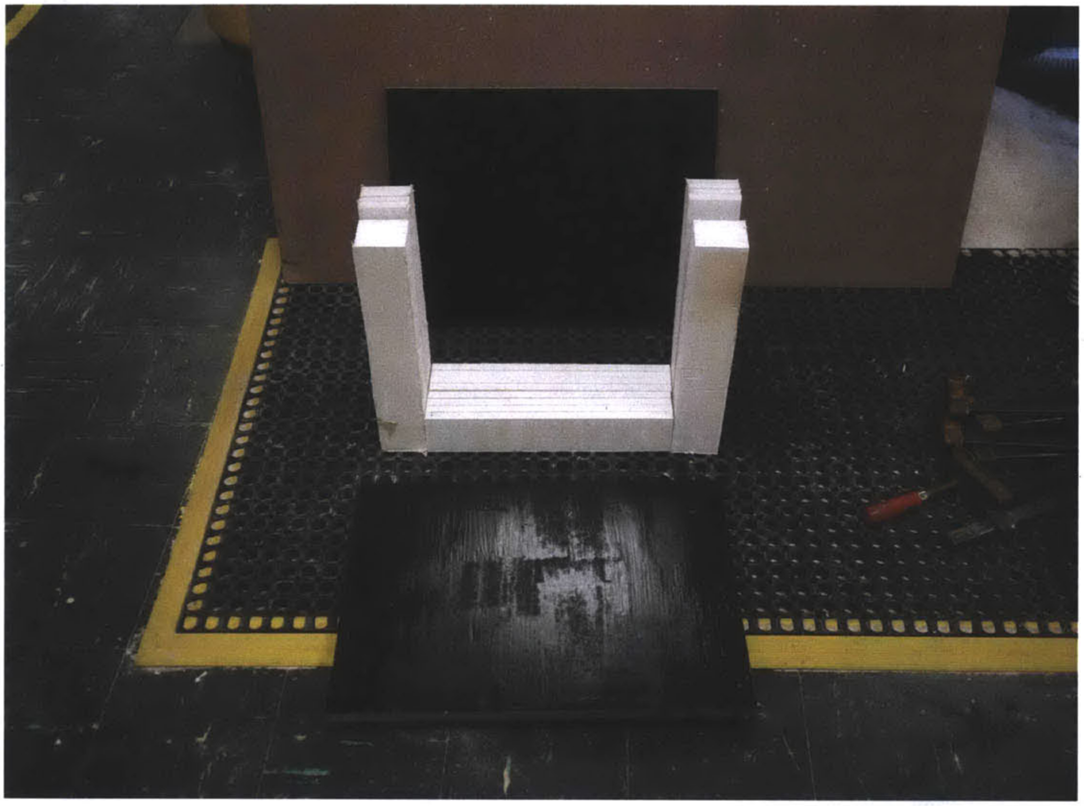

Plate 38
First gypsum mold under construction

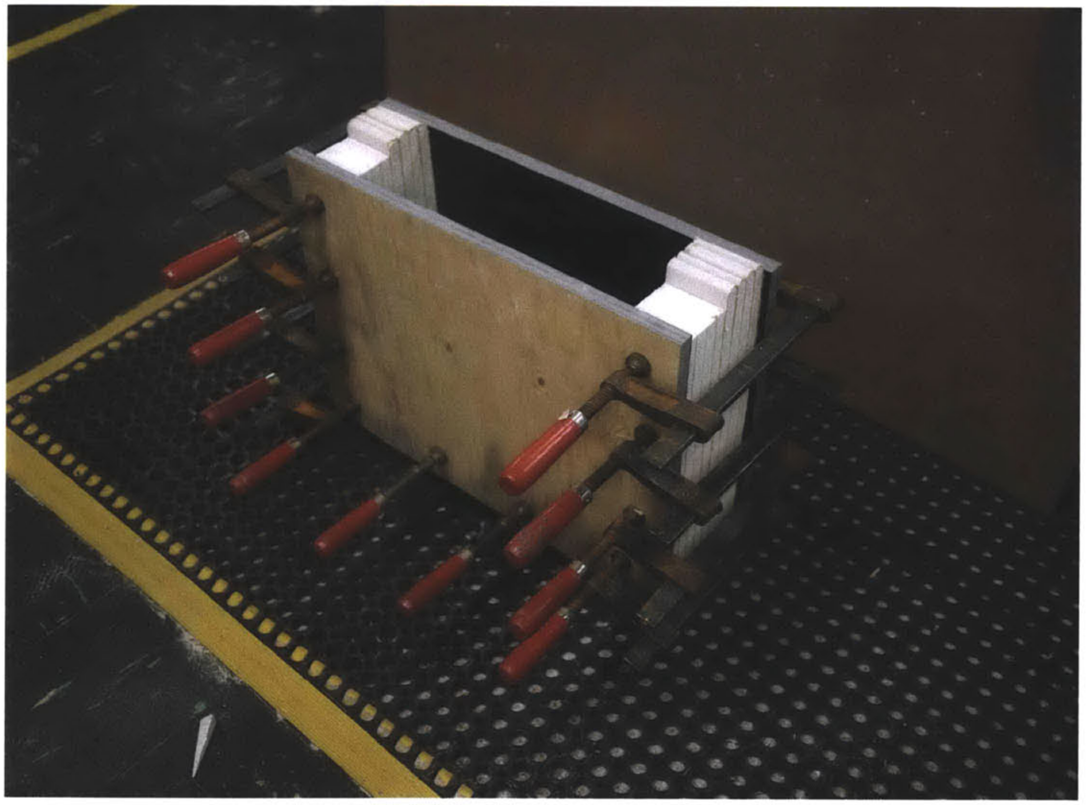

Plate 39
First gypsum mold ready for casting

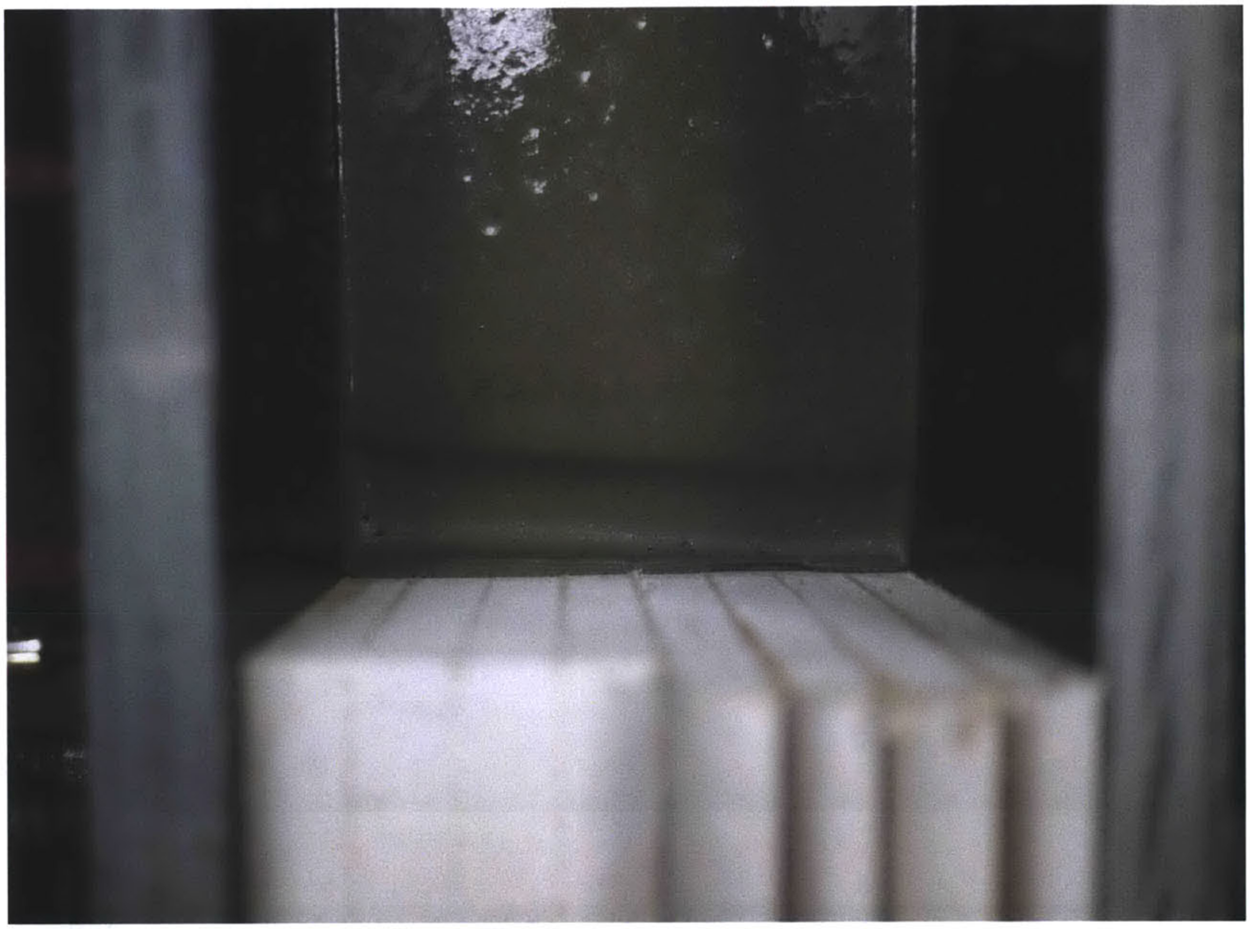

Plate 40
Retarded expansion visible at interface
between gypsum and aerating slurry

Plate 41
Partially demolded specimen cast in gypsum

Plate 42
Detail of specimen cast in gypsum

Plate 44
First beam prototype 30 minutes after pouring. Expansion of the matrix is visible. Non-expanded material is visible along the sides of the casting.

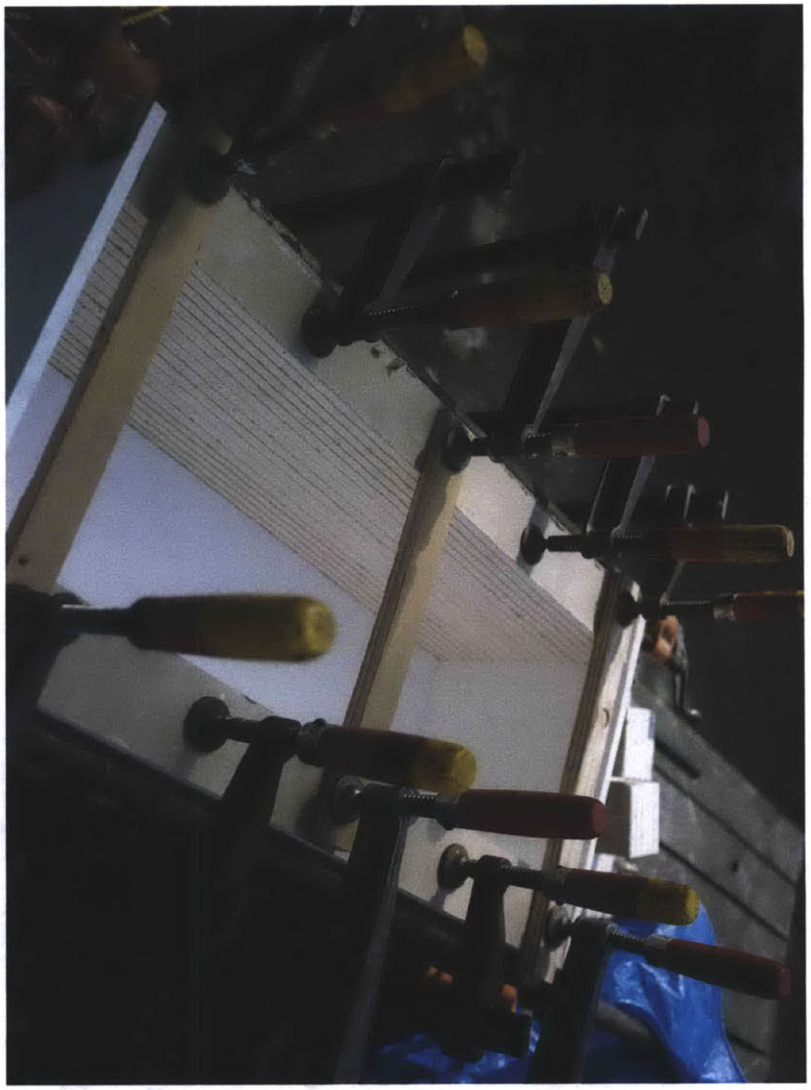

Plate 43
Gypsum mold set up for first beam prototype

Plate 45
Close-up of expanding slurry in the gypsum beam mold

Plate 46
After expansion has ceased

Plate 48
First beam prototype after demolding. The poor surface quality due to the interaction between the gypsum mold and the hydrating concrete is visible.

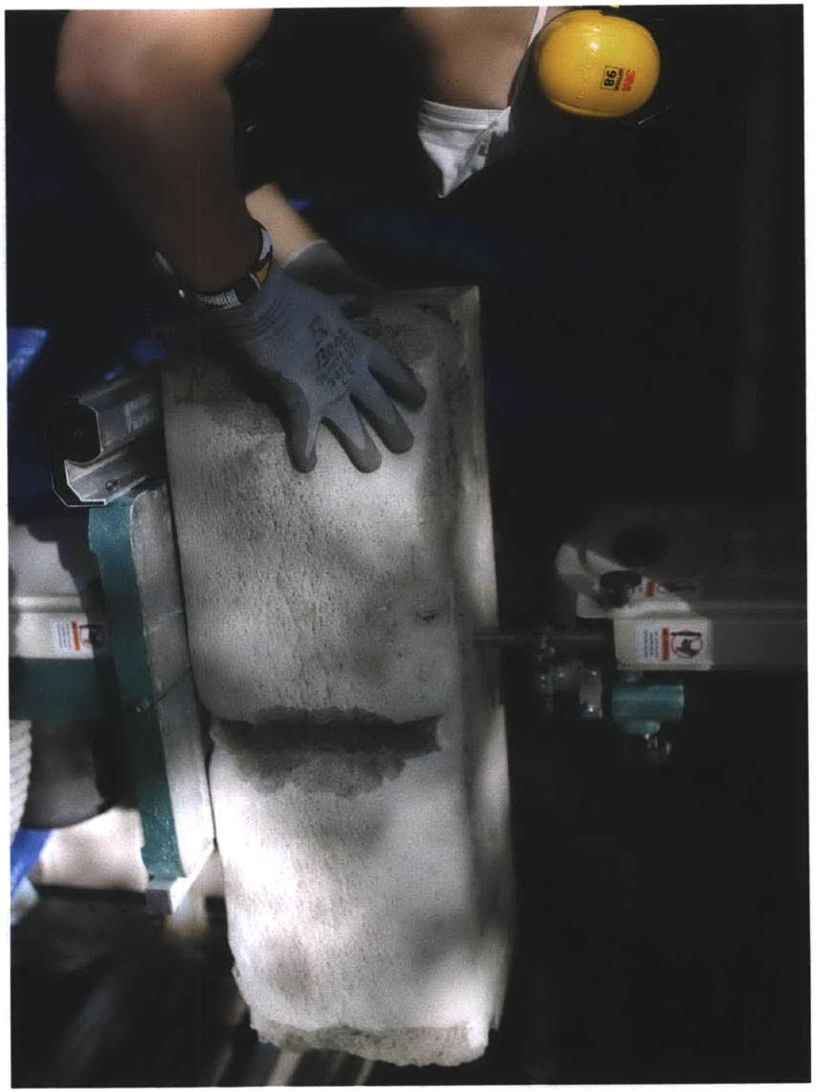

Plate 47
The beam being trimmed after demolding

Plate 49
First beam prototype after trimming and cleaning.

Plate 51
Second beam prototype being demolded.

Plate 50
Second beam prototype molding setup. Blocks of gypsum on the sides of the mold are wrapped with fabric.

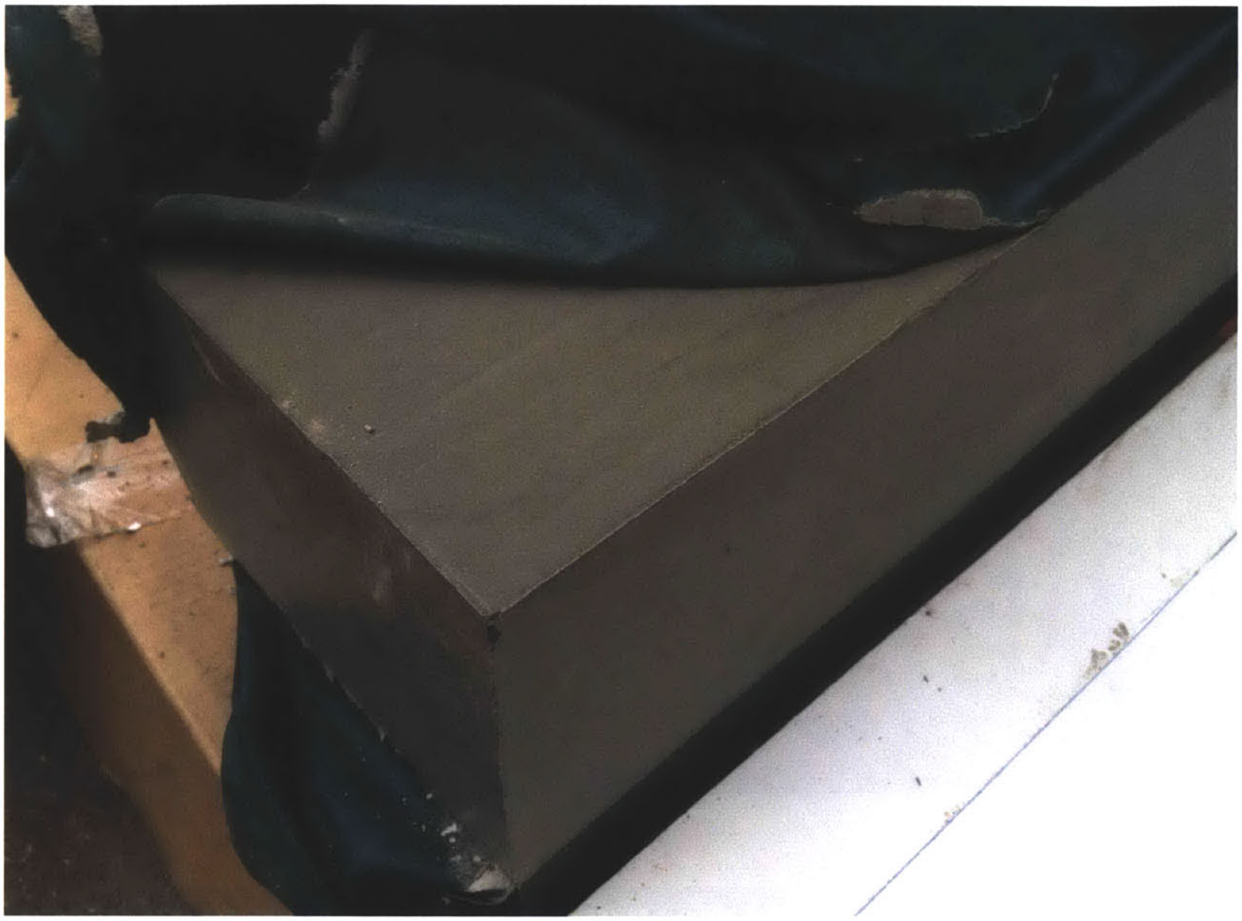

Plate 52
Second beam prototype being demolded. The high surface quality achieved through the use of a fabric liner is visible.

Plate 54
Non-aerated compression cylinder (specimen B2) exhibiting typical brittle fracture pattern (cone with vertical cracks running through the cap).

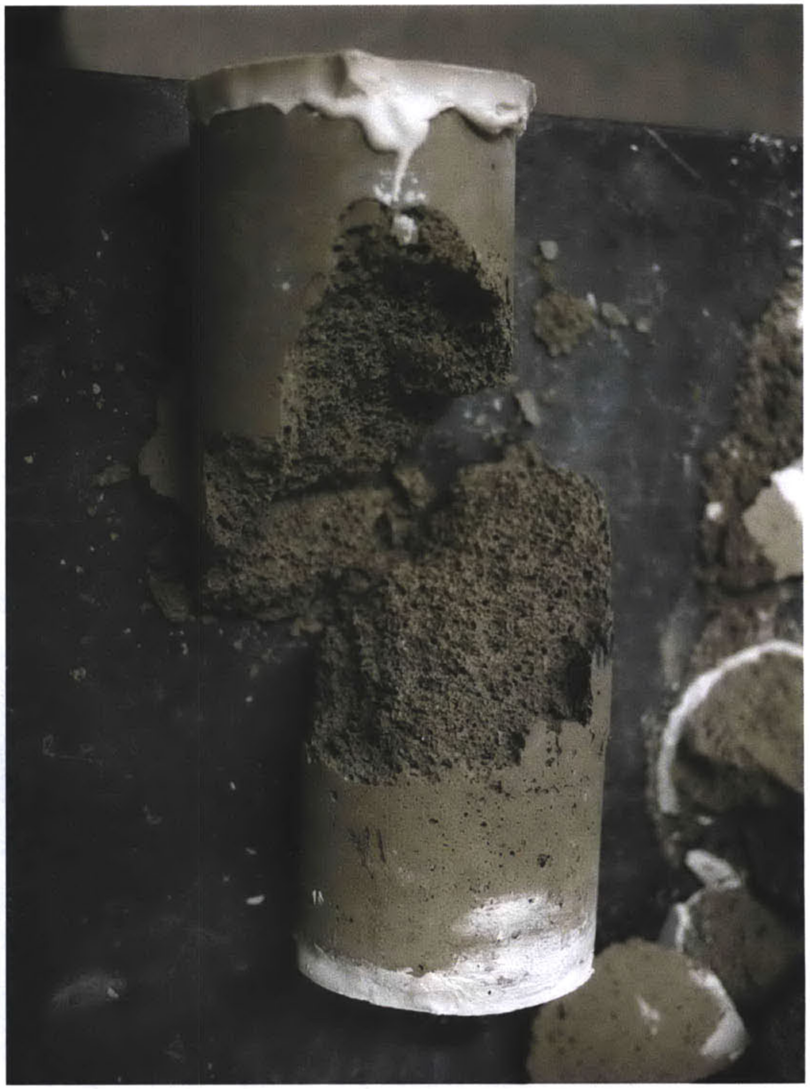

Plate 53
Aerated compression cylinder after testing (Specimen A1). Representative diagonal fracture pattern typical of brittle cellular solids is apparent.

Plate 55
Compression testing setup

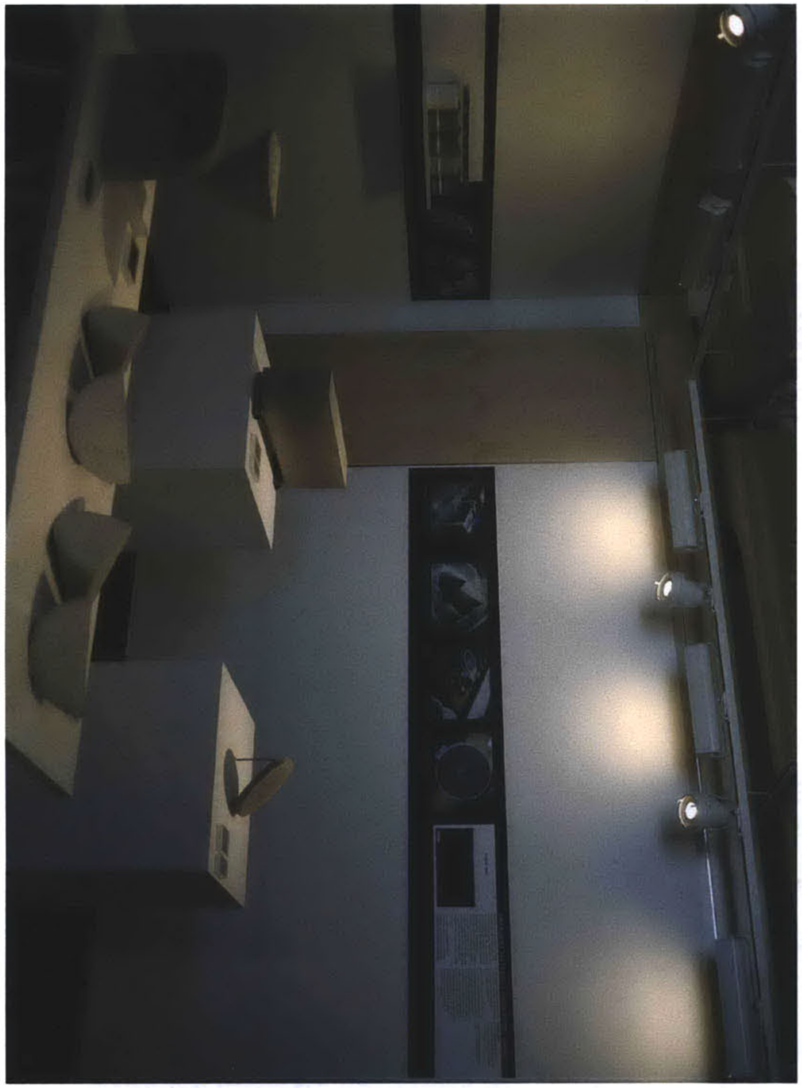

Plate 57
Exhibition of variable density concrete samples and prototypes at the
MIT School of Architecture and Planning Keller Gallery
Oct. 25th - Nov. 7th, 2011

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Exhibition of variable density concrete samples and prototypes at the
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Plate 59
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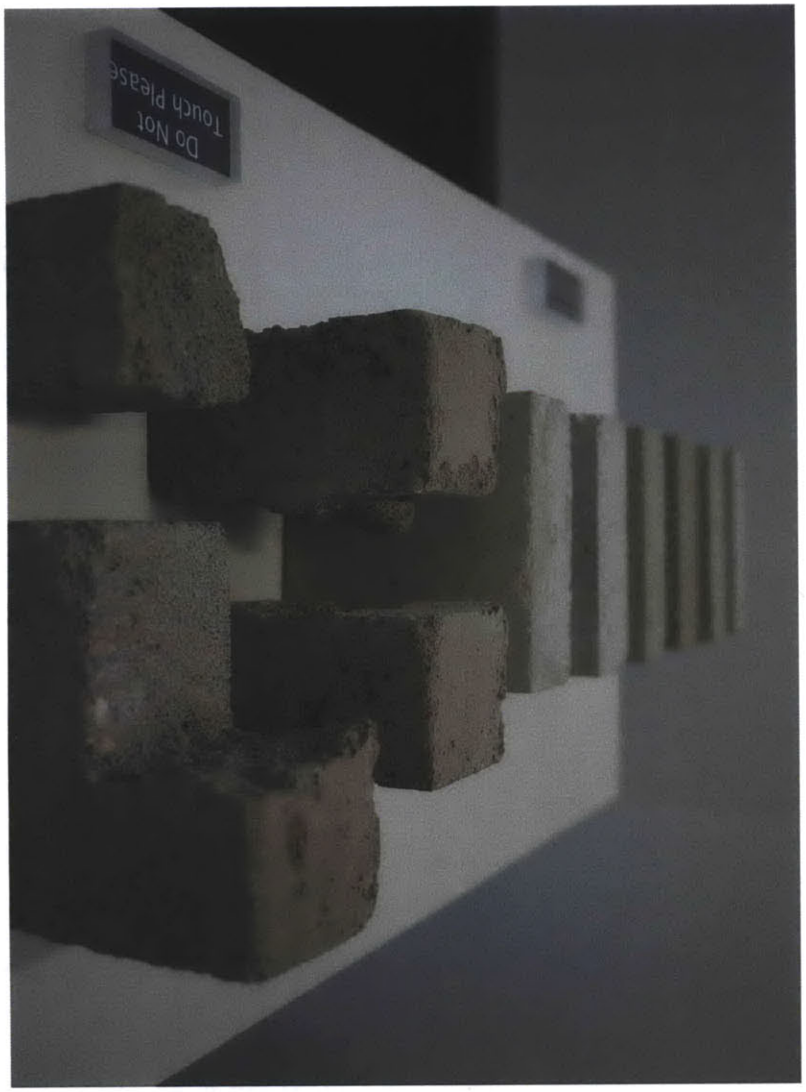

Plate 61
Exhibition of variable density concrete samples and prototypes at the
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Plate 62
Exhibition of variable density concrete samples and prototypes at the
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Oct. 25th - Nov. 7th, 2011

Appendix B
Materials and Equipment Suppliers

Material/Equipment	**Supplier**
Portland cement type I/II Quick lime	*Waldo Bros.* 202 Southampton Street, Boston, MA 02118 Tel: (617) 445-3000 www.waldobros.com
Fly ash	*Headwaters Resources* Stephen Berlo, Technical Sales Representative 183 Turner Road, Scituate, MA 02066 Tel: (781) 307-6334 sberlo@headwaters.com
Technical aluminum paste	*SCHLENK-Both Metallic Pigments* Thomas Schaller, VP Sales and Marketing 40 Nickerson Road, Ashland, MA 01721 Tel: (508) 881-9147 ext. 331 Cell: (508) 269-1972 Fax: (508) 881-1278 www.schlenk.com
Polypropylene meshes	*Sefar Inc.* 111 Calumet Street, Depew, NY 14043 Tel: (716) 683-4050 Fax: (716) 685-9469 filtration@sefar.us www.sefar.us
Gypsum wallboard tailings Misc. equipment	*Home Depot* 5 Allstate Road, Boston, MA 02125 (617) 442-6110 homedepot.com
Super-absorbent-polymer fabric	*Inventables, Inc.* 600 W. Van Buren #602, Chicago, IL 60607 Tel: (312) 775-7009 Fax: (413) 332-0054 help@inventables.com

Granular super-absorbent-polymer	*Willie E. (Skip) Rochefort, Ph.D., FAIChE* Associate Professor, School of Chemical, Biological, and Environmental Engineering (CBEE) Oregon State University Gleeson Hall 205, Corvallis, OR 97331 Tel: (541) 737-2408 Fax: (541) 737-4600 skip.rochefort@oregonstate.edu
Bandsaw (G0555 The Ultimate 14")	*Grizzly Industrial, Inc.* www.grizzly.com

Appendix C
Analysis Procedures and Experimental Mix Designs

Workflow for image analysis of prepared samples (sample preparation is described in Section 4.4).

–Scan uncompressed TIFF RGB color image with a resolution of 1200 pixels per inch obtained from a flatbed scanner (Epson Expression 10000XL)
–Open image file in Adobe Photoshop CS5
–Crop image to the boundary of the prepared sample
–Threshold image at gray value of 145 [Image>Adjustments>Threshold...](this value chosen to achieve best fit for the boundary between solid and void regions based on comparisons between thresholded images and original RGB images).
–Open thresholded image in ImageJ64.
–Change colorspace to 8-bit gray scale [Image>Type>8-bit]
–Remove noise [Process>Noise>Remove Outliers...]
    Radius: 3.0 pixels
    Threshold: 50
    Which outliers: bright
–Select image region to be analyzed [Edit>Selection>Select All]
–Analyze image [Analyze>Plot profile]
–Save profile data

Mix Designs for Casting Experiments

Column Tests #1 (2"x2"x12") and #2 (4"x4"x24")

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	3,000	62
Type I/ II Portland Cement	1,500	31
Quicklime	360	7
Aluminum Paste	8	0.16
Total Dry Constituents	**4,868**	
Water	**2,430**	

Column Tests #3 (2"x2"x24")

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	1,000	62
Type I/ II Portland Cement	500	31
Quicklime	120	7
Aluminum Paste	2	0.12
Total Dry Constituents	**1,622**	
Water	**810**	

Foaming Rate Test*

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	1,000	62
Type I/ II Portland Cement	500	31
Quicklime	120	7
Aluminum Paste	2	0.12
Total Dry Constituents	**1,622**	
Water	**810**	

*the majority of this batch was used to cast an additional gravity column (column #5)

Centrifugal Cylinder Test #1 and #2

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	3,000	62
Type I/ II Portland Cement	1,500	31
Quicklime	360	7
Aluminum Paste	8	0.16
Total Dry Constituents	**4,868**	
Water	**2,430**	

Centrifugal Cylinder Test #3

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	2,000	62
Type I/ II Portland Cement	1,000	31
Quicklime	240	7
Aluminum Paste	5	0.12
Total Dry Constituents	**3,245**	
Water	**1,620**	

Centrifugal Cylinder Test #5

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	4,000	62
Type I/ II Portland Cement	2,000	31
Quicklime	480	7
Aluminum Paste	9	0.14
Total Dry Constituents	**6,489**	
Water	**3,240**	

Centrifugal Cylinder Test #4

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	3,150	62
Type I/ II Portland Cement	1,575	31
Quicklime	378	7
Aluminum Paste	7.5	0.15
Total Dry Constituents	**5,110.5**	
Water	**2,551.5**	

Conical Fabric Tests #1, #2, #3

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	2,000	62
Type I/ II Portland Cement	1,000	31
Quicklime	240	7
Aluminum Paste	4	0.12
Total Dry Constituents	**3,244**	
Water	**1,622**	

Conical Fabric Test #4

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	1,478	37
0.15 mm quartz sand	1,000	25
Type I/ II Portland Cement	1,239	31
Quicklime	297	7
Aluminum Paste	6	0.14
Total Dry Constituents	**4,020**	
Water	**2,010**	

Cubic Mesh Tests

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	3,000	62
Type I/ II Portland Cement	1,500	31
Quicklime	360	7
Aluminum Paste	7	0.14
Total Dry Constituents	**4,867**	
Water	**2,430**	

Cubic Mesh Tests with Super-Absorbent-Polymers

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	3,000	62
Type I/ II Portland Cement	1,500	31
Quicklime	360	7
Aluminum Paste	7	0.14
Total Dry Constituents	**4,867**	
Water	**2,430**	
Super-absorbent-polymers	**400**	

SAP Fabric Test

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	3,918	60
Type I/ II Portland Cement	2,082	32
Quicklime	480	7
Aluminum Paste	8	0.12
Total Dry Constituents	**6,488**	
Water	**3,240**	

Gypsum Test #1

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	8,000	62
Type I/ II Portland Cement	4,000	31
Quicklime	960	7
Aluminum Paste	16	0.12
Total Dry Constituents	**12,976**	
Water	**6,480**	

Fabric-lined Gyspum Beam Prototype

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	20,000	62
Type I/ II Portland Cement	10,000	31
Quicklime	2,610	8
Aluminum Paste	45	0.14
Total Dry Constituents	**32,655**	
Water	**16,305**	

Gypsum Beam Prototype

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	28,000	62
Type I/ II Portland Cement	14,000	31
Quicklime	3,360	7
Aluminum Paste	64	0.14
Total Dry Constituents	**45,424**	
Water	**22,680**	

Thermal Test

Constituent Material	Quantity (grams)	% of Total Dry Mass
Class F Fly Ash	9,000	61
Type I/ II Portland Cement	4,500	31
Quicklime	1,179	8
Aluminum Paste	21	0.14
Total Dry Constituents	**14,700**	
Water	**7,340**	