USE OF RECYCLED OYSTER SHELLS AS AGGREGATE FOR PERVIOUS CONCRETE

By

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To the power of perseverance
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<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>ACI</td>
<td>American Concrete Institute</td>
</tr>
<tr>
<td>W/C</td>
<td>Water to cement ratio</td>
</tr>
<tr>
<td>A/C</td>
<td>Aggregate to cement ratio</td>
</tr>
<tr>
<td>PCC</td>
<td>Portland Cement Concrete</td>
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<td>AC</td>
<td>Asphalt Concrete</td>
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Increasing costs of transporting raw aggregate and the high demand of the construction industry on the Earth’s natural resources have led researchers to begin investigating alternate sources for concrete aggregates. Recycled content aggregate is one area that has gained popularity in that arena.

In this study, recycled oyster shells were used as an aggregate for pervious concrete. The shells used in this study were diverted from a local restaurant’s waste stream. It was found that the restaurant sent approximately 10,000 oyster shells to the landfill each week. The shells were cleaned and crushed and a pervious concrete mix design was developed. Six compactive methods were used to place the concrete including: vibrated, rodded, Standard Proctor, customized Standard Proctor and Modified Proctor, as well as non-compacted.

The results showed a potential for a viable pervious oyster shell concrete with appropriate compaction methods. Porosity ranged from 26-38%. Compressive strengths had a very wide range of 206 psi with a vibration-compacted sample to 1596 psi with a Modified Proctor sample. Permeability also had a wide range, with drainage rates of 27
gal/min/ft² with a vibration-compacted sample, to 0.3 gal/min/ft² with a Modified Proctor sample.
CHAPTER 1
INTRODUCTION

Research Overview

It has been estimated that Americans will use as much aggregate over the next 25 years as they did cumulatively over the whole of the 20th century (Langer et al. 2004). In 2007, the US led the world in non-fuel mineral mining and processing with values totaling $575 billion (Hitzman et al., 2009) The construction industry alone consumes about 70% of the overall mineral extraction in the United States in order to build and maintain commercial and residential structures, highways, bridges and parking lots.

The United States Geological Survey, in a 1998 report “Aggregates from Natural and Recycled Sources” defines the term aggregate as, “materials, either natural or manufactured, that are either crushed and combined with a binding agent to form bituminous or cement concrete, or treated alone to form products such as railroad ballast, filter beds, or fluxed material.”

Approximately three billion metric tons of aggregate are used in construction per year (Shulman, 2005). While this number may sound surprising, it may be rationalized when the following numbers are taken into account:

- It takes 38,000 tons of aggregate to make one mile of a four-lane highway.
- The American average single-family home requires 400 tons of aggregates to build.
- A 100,000 square foot office building requires 5,000 tons of aggregate (Wilson, 2008).
In one study by Purdue University, data were compiled showing that extraction of natural aggregates for the concrete and cement industry as being responsible for only 18% of the total waste and mining overburdens in 1996. Yet that small percentage was still a staggering 447 MMT (million metric tons). It was also estimated that the ratio is 6:1 for the ratio of total raw material moved to a given volume of concrete (Low, 2005).

Aggregates are generally mined or quarried from more than 9,000 pits and quarries across the country. (Shulman, 2005) Though it may stand to reason that the Earth is made of rock therefore aggregates should be a relatively easy material to acquire, this is not always the case. Some areas may have a high water table and make extraction expensive. Other areas may have a good deposit of limestone, for example,
but its source is at such a depth as to make it impractical. Some aggregates simply may not react well chemically when used in applications such as concrete or asphalt.

Transporting aggregates generally has a high cost impact, so being close to urban centers has significant economic benefits. There are, however, many environmental concerns associated with establishing a mine or quarry near a densely populated locale.

Some of these concerns include:
- Increased dust, noise and blast vibrations
- High density of transport truck traffic
- Physical landscape changes and wildlife habitat disturbances
- Possible pollutants added to groundwater and soil
- Emission of greenhouse gases into the air

There are alternatives to using only raw material aggregates in construction. The use of recycled aggregate is one way to potentially extend the life of natural resources by supplementing their supply, reduce the environmental impact of material extraction, as well as the impact of construction demolition in landfills. According to a U.S. Environmental Protection Agency study, construction and demolition waste totaled more than 135 MMT in 1998. Of that amount, as much as 75% could have been diverted to recycling centers (Kibert, 2005).

Recycled aggregates are obtained by crushing concrete and often asphalt. Recycled aggregate comes primarily from Portland cement concrete (PCC) and asphalt concrete (AC). The concrete in its original state generally comes from road rehabilitation, maintenance or demolition, structure demolition, and leftover batches of AC and PCC.

Recycling of construction aggregate is most common near urban areas where constant replacement of infrastructure is necessary, natural resources are limited or
uneconomical to bring in, demolition disposal costs are high or regulations, be they local or federally mandated environmental policies, prevent their disposal (Wilburn et al., 1998).

Aggregate recycling centers are increasing in number, but the demand is great and the supply slow. Approximately only 5% of the 3 billion metric tons (BMT) of new construction aggregate used in 2005 was comprised of recycled aggregate (Shulman, 2005). This number can be expected to rise with the public demand for more sustainable materials becoming an ever-increasing factor in materials acquisition, concrete and asphalt mix designs becoming lighter, stronger and cheaper with the inclusion of recycled content, and the introduction of portable, on-site recycling centers.

Other options in the recycled aggregate market aside from post-construction concrete or asphalt are constantly being introduced. Post-consumer glass, fiberglass pellets, plastics, even old tires are making a more pronounced presence in the aggregate arena. However, there are obstacles for these recycled aggregates to overcome as well. For example, glass must be sorted according to color, broken into smaller pieces then crushed, sorted and cleaned or in some cases, melted.

Fortunately, much of the construction industry’s uses for glass aggregate do not require the labor- and time-intensive sorting process. In 1993, New York City collected 27,000 tons of mixed waste glass and used it to produce glasphalt- a 90% asphalt and 10% glass composite mixture (Michigan Technological University, 2003).

The majority of the alternative recycled aggregates are derived as a post-consumer resource, which means that public participation is vital. This is perhaps the biggest setback to alternate aggregates. In 2007, Americans generated about 254
million tons of trash, of which only 85 million tons were recycled or composted (EPA, 2007). This is the equivalent of a 33.4% recycling rate - an 8% increase from the 26% reported in 2002. It is expected that this rate could climb to as high as 60-80% with energy prices for production continuing to rise and national resources facing depletion (Chiras, 2002).

Conclusion

The success of recycled construction aggregate and alternative aggregates depend largely on the involvement of the individual; without the consumer, there would be no post-consumer content. And the consumer is not just the average citizen disposing of their trash and deciding to sort it into recycling bins; it is also the building owner who demands materials used on their jobsite that incorporate a certain percentage of recycled content; and it is the aggregate company that begins to offer more recycled content options. It is also about the government instituting policies that help ease the transition as non-conventional aggregates take a more active role in the construction industry.

Goals and Objectives

This study evaluates the potential of the Eastern Oyster shell as a recycled aggregate, as well as seeks to develop a pervious oyster shell concrete mixture that is a viable, sustainable building material. It is the intent of this research to create as little environmental impact as possible during the course of this study. It is also the intent of this study to create an uncomplicated mix design, which may be of particular use to individuals and small-scale projects.
CHAPTER 2
BACKGROUND

Oyster Shells in Construction

Quicklime

Perhaps one of the oyster shell’s most popular uses in construction throughout history has been in its burnt form as lime, also known as quicklime. Documentation of oyster-based lime dates back several thousand years and crosses many nations and continents including Honduras, Brazil, Greece, Northeast India, and Australia.

One early American reference to lime burning is found in *Mechanick Exercises* by Joseph Moxon, published in 1703. Moxon detailed his theories on the various trades including carpentry, and bricklaying. In his discussion on lime, he states, “But the shells of Fish, as of Cockles and Oysters are good to burn for Lime” (Sickels-Taves, 1996).

To make quicklime, a pit was excavated and filled with wood, preferably pine or heart pine. Once the pit was completed a small log structure, also known as a rick, was built on top. This rick contained several tiers of logs within which were held smaller layers of logs covered with oyster shells. The entire structure was set ablaze and allowed to collapse upon itself. Interior temperatures reached approximately 2000°F. These high temperatures were necessary to ensure the proper chemical reactions necessary to convert the calcium carbonate of the shell into the calcium oxide of lime (Sheehan et al., 1998).

Tabby

Lime obtained from oyster shells first appeared in mortar mixes during the Middle Ages, apparently originating in North Africa and Spain. This mix (and similar mixes using on-hand aggregates) was given several names: *pise* in French influenced areas,
tapia (meaning mud wall), in the Spanish-speaking world, tabya in Islamic countries and tabby in the British world. The latter is the most commonly used name, and its origin could be an adaptation of tapia or the Arabic word tabbi, which means a mixture of mortar and lime. There are also similar words appearing in both Portuguese and Gullah. (Morris, 2005)

Tapia was said to be one of the most common building materials of the 15th century Cordoba and Seville and a standard construction method in many Muslim territories in the 13th century, especially for military purposes. (Deagan, K. 2002)

There are even several examples of buildings made out of oyster shells using a tabby material in China. These homes are called Erkecuo houses and can be dated back to the Qing dynasty (1644-1911). It is believed that the oysters used in the Erkecuo homes were from Africa because the shells are approximately 3-5 times larger than local shells. Historians propose the shells were used as ballast on trade ships returning back to the port of Xunpu. The Xunpu village was on the Maritime Silk Road, trading silk, tea and pottery (WOX Info, 2009).

The most common examples, however of tabby-like structures are from Europe. One example of British tabby building is the Wareham Castle, in Dorset, England dating from the early 11th century. The building is in ruins, but was excavated in the 1950s by H.J.S. Clark (Renn, D.F., 2009). The castle is now a unique structure for the British, as disease has all but destroyed their oyster industry.

When the Spanish and English began to build up the American colonies they carried the art of oyster concrete with them. There were two primary centers for its
distribution: British-built tabby arising out of Beaufort, South Carolina while Spanish traditions were derived from St. Augustine, Florida (Adams, D., 2007)

![Barn of tabby construction on Kingsley Plantation, St. George Island, Jacksonville, FL.](image)

Figure 2-1. Barn of tabby construction on Kingsley Plantation, St. George Island, Jacksonville, FL.

James Oglethorpe, a British officer stationed in South Carolina in the early 1700s is credited with bringing tabby into Georgia. Oglethorpe believed it to be a logical material with which to build fortifications. Therefore, with his backing forts, support structures, and even his own home were built out of tabby. However, with the Treaty of Aix-la-Chapelle in 1748, the threat of Spanish invasion ceased, and the use of "Oglethorpe tabby" diminished.

Approximately 90 years later, another advocate of tabby would arise by the name of Thomas Spalding. Spalding’s father had purchased Oglethorpe’s “Tabby House” and Thomas had been born there. Tabby from that era is often called “Spalding Tabby.”

Spalding built a home and many other structures on Sapelo Island, Ga, where he was a prominent businessman. His house is also referred to as the Tabby House or the Ashantilly house. Spalding kept copious notes and journals regarding the building methods, seed cultivations and farming techniques employed at the time. In addition, he
promoted the use of Tabby in local publications and other various periodicals. These writings provide some of the most detailed information available regarding the history of Tabby. In one article, Spalding wrote, “Tabby is a mixture of shells, lime and sand in equal proportions by measure and not weight and makes the best and cheapest buildings, where the materials are at hand, that I have ever seen; and when rough cast equals in beauty stone,” (Sullivan, B., 1998).

Figure 2-2. The Ashantilly House, Sapelo Island, GA.

The spread of tabby throughout the south between the early 1800s and the mid-1800s was largely tied into the creation and expansion of plantations. With the onset of the civil war, the use of tabby waned. After the war, the traditional method for making tabby was altered because of the introduction of Portland cement to the United States. The use of Portland cement negated the need for lime and was preferred because it completely removed the arduous task of burning oyster shells from the tabby process. Tabby made with Portland cement is most commonly referred to as Tabby Revival and was used, though in much smaller amounts, between approximately 1870-1925 (Sickles-Taves, 1999).
By the end of the 19th century, the use of tabby as a building material was almost nonexistent. There are several factors that appear to have been significant in its decline: first, construction of new buildings severely declined during Civil War years; second, the breakdown of the plantation system denied owners the plethora of unskilled workers necessary for the labor-intensive process; and third, the introduction and easy availability of Portland cement and readymade concrete blocks.

Traditional tabby is a slurry of equal parts lime, sand, water and shell. These materials are measured by volume, not weight. Thomas Spalding wrote his formula as “10 bushels of lime, 10 bushels of sand, 10 bushels of shells and 10 bushels of water” to yield 16 cubic feet of wall. He made walls on average 14 inches thick. Those beneath the ground were 24 inches and the second story walls were 10 inches; he would not erect tabby buildings beyond two stories (Adams, D., 2007).

The tabby slurry was poured into wooden cradle forms that were held together by round pins. Early tabby forms were generally 20-22 inches in height but by the 19th century were reduced to 10-12 inches to reduce chance of collapse and provide greater strength (Sickles-Taves, 2008). Once in the form, the slurry was hand tamped and leveled. The tabby was then air dried in its cradle for several days before the next layer was added on top.

Although generally poured into wall forms, tabby can be formed into many various architectural features. By crushing the oyster shells, smaller wedges and bricks could be made, with a tabby mortar employing finely crushed shells used to cement them together.
Tabby is a very porous material and meant to be covered by stucco for protection. Traditionally, the stucco mix is just a thicker mixture of the tabby but without the oyster shells, however, stucco containing crushed shells have been documented.

![Image of tabby concrete through cracks in stucco facade](image)

Figure 2-3. Tabby concrete shown through cracks in the stucco façade.

Cracks in the stucco façade resulting from settling over time or weather damage such as hurricanes, improper application of the stucco or lack of maintenance can all be causes of stucco’s failure to prevent water intrusion into the tabby material. Trenching around the foundation of a structure and filling it with oyster shells was one way to further the life of a stucco coating as the shells would wick away moisture from the base of the walls.

It is a paradox for tabby to be a very porous material yet be native to salty coastal areas. Fortunately, the tabby can generally control the absorption and evaporation with the help of the warm climate. This process is significantly slowed or even brought to a halt if incompatible materials are introduced onto the tabby that makes it impossible for this cycle to continue.

Such was the case with the Oglethorpe Tabby House on Cumberland Island, Ga. In the early 1990s, neat cement had been added as a stucco layer to the surface of the
tabby. It was soon discovered that the tabby couldn’t “breathe.” The walls began to buckle, mold and mildew appeared and paint began to peel on interior walls. The National Park Service was forced to install a 24-hour fan to circulate air until the “repairs” could be mitigated.

Dr. Lauren Sickels-Taves, an expert on the care and preservation of tabby, did numerous studies on the Tabby house. The three of the tests she ran were the particle-induced X-ray emission (PIXE) test, an optical stereology and an ash analysis. The PIXE test provided a chemical analysis of the tabby, the optical stereology identified the sand used in the mix as deposits from a local channel, and the ash analysis confirmed the inclusion of wood ash from the lime rick (Sickles-Taves, 2008).

During testing, Sickels-Taves also took core samples from some of the original tabby and compared it to a sample of tabby made in the laboratory. The results were as follows:

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<tr>
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<th>Original Tabby</th>
<th>New Tabby</th>
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<tr>
<td>Compressive Strength (psi)</td>
<td>350</td>
<td>320.5</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.013</td>
<td>2.203</td>
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Using these tests, Sickels-Taves identified the formula for the Oglethorpe Tabby House as a 1:3 lime: sand with wood ash, obtained during the process of burning the oyster shells. This specific formula is, perhaps ironically, one of two formulas for concrete specified by the ancient Roman Marcus Vitruvius Pollio in his famous work dated 4630 BC, The Ten Books of Architecture (Sickels-Taves, 1998).

**Shellcrete**

Another historic oyster concrete is called shellcrete, indigenous to Spanish Texas and popular in the mid-1800s. Shellcrete was made by creating bricks out of a mixture
of crushed shells, lime, water and thick, white local clay. A small amount of sand was
used to temper the clay if necessary. The mixture was tamped into sand-dusted forms,
sun-hardened then baked in a firewood-heated kiln (Givens, 2006).

One example is the Centennial House, also known as the Forbes Britton House, in
downtown Corpus Christi. Built in 1849, the home’s stout 3-layer brick construction
has reportedly provided shelter to the town’s inhabitants through many hurricanes and
even Mexican bandit raids (Cox, 2006).

Figure 2-4. Centennial House, Corpus Christi, TX.

Roads

As the demand for oyster shells was decreasing in the home building industry, it
was increasing elsewhere in the world of construction. One 1894 U.S. Department of
Agriculture public road bulletin praised the shells’ value and its cementitious capacity.
The author sited large midden piles as a near-endless resource for aggregate (Stone,
1894). However, when those supplies ran out, Florida began dredging coastal
waterways for shells. Those oyster shells were pulverized then used as a main
ingredient in highway paving for many years in Florida. This practice was in use until the
mid-80s, when legislation called for its halt due to the detrimental nature of dredging (Berrigan, 2009).

**Current Uses**

In Florida at this time, 50% of all commercially harvested shells, with the exception of those sent to half-shell restaurants, must be returned to the state for its reef reconstruction program (Florida Statues Title XXXV, 2009). The remainder of all shells may be sold to the highest bidder, which is most commonly the poultry feed industry.

Many coastal residents choose to use oyster shells as pavement for driveways. The shells are often just placed on the ground and not mixed with any cementitious material. Also, some enterprising individuals have begun creating artificial fish tank structures out of crushed shells. And there are even some who go the extra mile and use a modern tabby formula to recreate the old style as closely as possible while successfully maintaining modern code standards.

**Pervious Concrete**

**History**

In addition to the search for new or more sustainable aggregates for concrete is also the quest for a more environmentally friendly pavement. One option that is becoming more popular called pervious concrete. A relatively new material in the US, pervious concrete first appeared in the United Kingdom in 1852 as a structural material for building homes, then later as a pavement in the mid-1960s. In the US, it has acted as an environmentally friendly alternative in stormwater management practices, a champion for fertile, tree-lined parking lots and a friend to those in need of a sturdy, non-slip surface for more than 20 years.
Pervious concrete, also known as no-fines or gap-graded concrete was a very popular building material in Europe during the post-World War II construction boom. Both skilled labor and building materials were in short supply so an English man named George Wimpey developed a method that required men with little or no skill to erect forms and place no-fines concrete to build 2-story homes (Offenberg, M., 2008). It is unknown when pervious concrete was first introduced into the United States, though the earliest documented pervious concrete pavement at this time dates back to 1985. The National Ready Mix Concrete Association (NRMCA) is currently compiling a record of all U.S. pervious projects. The database now lists approximately 250 entries with more than 60% in the Southeastern states and 20% in California. The rest are spread across the country and include states such as Illinois, Pennsylvania, Ohio and Vermont (Kresge, 2009).

**Composition**

Pervious concrete is a composite material containing Portland cement, water, coarse aggregates and little or no fine aggregates, that allows water to pass through it. There is generally no slump and a very low water-to-cement ratio, as well as a low aggregate-to-cement ratio; usually just enough to provide adhesion of the aggregate but not enough to lose porosity. These low ratios contribute in part to pervious concrete being both a lightweight and sustainable product, as fewer materials are necessary for its manufacture.

Being held together at contact points by the thin cement paste is what gives pervious concrete its voids. Average void contents range from 20-30% depending on what type of aggregates or compaction techniques are used (Kosmatka et al., 2002). Voids and compaction methods also determine the permeability of pervious concrete.
There is a wide range of acceptable drainage rates, which are based for the most part on its intended application. An ACI R-06 report on pervious concrete states that drainage rates may vary between 2-18 gal/min/ft². Compressive strengths in pervious concrete are also quite variable and can range from 400 psi to 4000 psi.

Figure 2-5. Pervious concrete.

**Applications**

Pervious concrete can be used in a wide range of applications throughout the construction industry. Perhaps the most popular use in the U.S. is as pavement for light-traffic volume parking lots and sidewalks, though it has become more prevalent in stormwater systems. Pervious concrete has also been developed that is highly effective for use as flooring in greenhouses, as well as artificial reef structures (ACI R-06, 2006).

Use of pervious concrete as a pavement is considered an environmentally sound approach to the challenges that face many builders and owners when faced with stiff local and federal stormwater run-off regulations. Currently, the EPA requires owners of sites of 1 acre or more development to have an on-site stormwater management system in place. This often leads to 10-20% of the gross buildable area dedicated to non profit-generating features such as holding ponds or swales (Huffman, 2005). Because the
EPA considers pervious concrete a “Best Management Practice,” those large percentages can be significantly reduced by combining the parking lot with the stormwater treatment system.

![Figure 2-6. Pervious pavement parking lot.](image)

Pervious concrete is dubbed a stormwater treatment system in part because of the way it virtually eliminates the first-flush action of normal pavements. After heavy rains, the first flush sends surface toxins and pollutants along the pavement’s horizontal surface and into the nearest drainage outlet, then eventually streams and lakes. With a pervious concrete system, rain water does not pool or pond, nor does it allow water to rapid flow across its surface. Instead, the water and surface toxins drain through the concrete, then into the sub base and eventually into the soil below where further filtration may take place. This process provides a water purification system for stormwater runoff, as well as a groundwater recharge.

As it was stated earlier, one of the most popular applications for pervious concrete is as a pavement. There are many benefits to using pervious concrete as a pavement instead of conventional asphalt, including:
• Reduced glare means better visibility
• No puddles or standing water leads to less dangerous hydroplaning
• Larger air voids prevent pumping action, thereby reducing tire temperature
• Better sound insulation means less road noise
• Popcorn-like texture gives tires a better grip on the road

LEED

Pervious concrete’s “green” characteristics often help earn buildings high ratings in several LEED categories. Leadership in Environmental Energy and Design (LEED) is the green-building standard in the United States and Canada that was developed to give professionals a template from which to identify and implement sustainable building planning, design, construction, and maintenance practices. Potential LEED points for pervious concrete use may be available in the areas of stormwater management, landscape paving, minimizing energy use, recycled content, use of regional materials, site-wide VOC reduction, reduction in the use of Portland cement, and innovation in design.

To qualify for category MR 4.1 & 4.2, it is required that the sum of post-consumer recycled content plus one-half of the pre-consumer recycled content constitute at least 10% or 20%, respectively, (based on the dollar value of the material) of the total value of materials in the project. The requirement for post-consumer content is easily met with oyster shells, as they are directly diverted from the public waste stream. However, if following the mix design as tested for this research, the pre-consumer requirement would not be mixed. This could be resolved during future research with the addition of supplementary cementitious materials such as fly ash or blast furnace slag, which are pre-consumer recycled material.
Standards

With the rise in popularity of pervious concrete has come the need for quality control. Currently the ASTM Subcommittee C09.49 on Pervious Concrete has been reviewing a wide range of test methods developed all across the world. Members of the committee have been reviewing procedures for compressive strengths, flexural strengths, in-place permeability and in-place density/porosity. The Subcommittee released ASTM C1688 in late 2008, which provides a standard method for testing the unit weight of fresh pervious concrete.
CHAPTER 3
METHODOLOGY

Materials

Oysters

The aggregate used in this project is shell of the Eastern Oyster (*crassostrea virginica*), which is found in the American Atlantic and Gulf waters. This species of oyster is the most commonly found variety in the Southeastern United States and is predominately the only one sold at half-shell restaurants.

Cement

The cement chosen for this project was Type I Portland cement, which is perhaps the most common type of cement available on the market today. This product was chosen primarily for its easy accessibility, economic appeal, as well as its general durability.

Water

Only potable water adhering to ASTM C1602 was used in this research.

Oyster Shell Acquisition, Cleaning and Crushing

Acquisition

Several methods were attempted in the effort to obtain a large quantity of shells. Fliers were distributed to various University of Florida buildings as well as nearby businesses, requesting anyone with waste shells to deliver them to a designated drop-off or call for pick up. No shells were obtained through this method.

Several Gainesville seafood wholesalers were approached only to find that they are not legally allowed to shuck their own oysters.
It became clear that the remaining method of obtaining oyster shells was to rely on a half-shell restaurant. In Gainesville, FL, which is not a coastal community, there is only one restaurant of considerable size and that is Calico Jacks (CJ’s). Upon communication with the restaurant's management, it was learned that approximately 10,000 are shucked and consequently sent to the landfill each week.

CJ’s agreed to allow a separate trash container be placed behind their building and committed their shuckers to dumping the waste shells into the bin. After several weeks, the bin was not very full. Upon observing the shuckers at work, it was noticed that in the fast-pace of their shucking, they often forgot to separate the shells from the regular trash. As a result, accumulating a large enough quantity of shells for testing was a long process.

One technique the author tried that was successful was to collect the shells in person at the restaurant as the patrons and the shuckers were finished. This was time consuming, but having a presence at the restaurant seemed to help immensely.

Cleaning

One of the goals of this research was to make as little environmental impact as possible. With that in mind, several methods were tested in order to effectively clean the shells.

The shells were first rinsed thoroughly then laid out in the sun for several days. This method was not very effective, producing an extremely unpleasant odor, as well as ineffectively removing remaining oyster meat and miscellaneous food items such as cocktail sauce.

The shells were then soaked in a solution of bleach water for several days. Though this was more effective in removing some of the odor, it did not entirely remove
the meat and miscellanea. The shells were then tumbled in a concrete mixer with bleach, water and different abrasives such as sand, #89 pea gravel and #67 limestone. Of all the combinations attempted, using two shovels of pea gravel with the bleach water did prove reasonably effective in cleaning the shells; however, it did not adhere to the environmental standards of the project.

A different batch of oyster shells were first thoroughly rinsed in clean water then placed in a concrete mixer with a strong water and white vinegar solution, as well as two shovels of pea gravel. This mixture was allowed to turn for 30-45 minutes. The pea gravel was then sifted out, the shells rinsed off and then left to soak for approximately 48 hours in a baking soda bath. The resulting shells had no meat or miscellanea and little or no odor.

Figure 3-1. Shell cleaning. A) Fresh shells were mixed for approximately 30-45 minutes in a mixture of pea gravel and vinegar. B) Once rinsed clean of vinegar and gravel, shells were left to sit for 48 hours in a baking soda bath.

**Crushing**

The shells were required to pass between the ½ and #8 sieves, this would require the shells to be crushed. Several methods were used to crush the shells including mechanical and manual.
The clean, dry shells were taken to the local Florida Department of Transportation materials testing facility and run through an adjustable mechanical jaw crusher. The shells were dropped through a top slot and pressed against an iron plate with a separate movable plate. The resulting crushed shells fall into a collection bin. However, because of the flat nature of the shells, it was found that they often slip past or between the movable plate. This resulted in whole or nearly whole shells in the collection bin. It was also found that, unlike limestone that crushes into smaller rocks, oyster shells tend to flake and shear resulting in shells that were their original length and width but not depth. Many of the shells had to be run through several times to achieve a small enough size.

Figure 3-2. Crushing shells at the Florida Department of Transportation Materials Research Lab.

There were several occasions when it wasn’t possible to access the DOT machine. Hand tools such as hammers, sledgehammers and myriad other heavy objects found around the Rinker lab were used to crush the shells. The clean, dry shells were placed between layers of plastic for containment then pounded with the various tools. This did crush the shells, though at a much slower rate. Often, the sledgehammer
would pulverize the shells or not break them into small enough pieces, and often did both at the same time. Obviously, this is a very time consuming process and was not capable of producing a large quantity of shells, but did suffice for providing enough shells for testing purposes.

The only other process to mass crush shells that was tried was to run them over with a Caterpillar 226B Skid Steer Loader. Clean, dry shells were placed in two rows, one for each side of the tractor, on a concrete driveway. The tractor then repeatedly drove over the shells, using its weight of 5,800lbs to crush them with the tires. After the shells were collected, a large amount of foreign matter was found to be mixed in, apparently from the driveway and the tractor tires. These shells had to be well rinsed and sifted to remove all debris.

![Figure 3-3. Using a Caterpillar Skid Steer for oyster shell crushing. A) Oyster shells on bare concrete. B) Oyster shells encased in thick plastic to prevent contamination.](image)

The larger shells were sieved out, cleaned and dried then placed between very thick layers of plastic. Once again the tractor was used to repeatedly run over the shells. The tractor’s tires were sprayed down with water to prevent any dirt or debris that may
penetrate through the plastic. This time because the shells were protected by plastic and the tractor tires had been rinsed of surface dirt, they remained clean.

**Pervious Concrete Mix Design**

**Introduction**

Over the course of this research, several methods to attain a pervious oyster shell concrete mix design were implemented. During the first stages, less traditional techniques were used. The later phases followed more conventional practices. It should be noted that there are very few acknowledged standards for the development and testing of pervious concrete from national entities such as the American Concrete Institute (ACI) or the American Society for Testing and Materials (ASTM). As a result, many methods used are either based on similar concrete standards (such as lightweight concrete), or are the result of scientific hypothesis.

**Sieve Analysis**

Sieve analyses were run to determine the particle size distribution of each specific aggregate. Depending on what was desired for a mix design, particular sieves may be added or removed to accurately assess what range was needed.

Testing was performed in accordance with the ASTM C136 procedure for coarse aggregate. To achieve an accurate and diverse sample of oyster shells, the crushed pieces were spread evenly into a large oval onto a concrete surface that had been cleaned of all debris. The shells were then divided into quarters then opposite sections removed. The remaining sections were mixed and the procedure repeated until approximately 2000g remained. The shells were then placed into a mechanical sieve shaker, which held a designated nest of sieves. The shaker was run for 10 minutes, allowing sufficient opportunity for the shells to reach the bottom. Over the course of this
research, several sieve analyses were run and different sieves were added or removed from the nest to accommodate large or smaller openings.

After the shaking was complete, individual sieves were weighed to determine how many shells remained in each. From these calculations a particle size distribution and fineness modulus was determined.

**Unit Weight**

Testing for the unit weight of crushed oyster shell was done in accordance with the ASTM C29 procedure. A random sample of shell was oven dried to 100°C then cooled to room temperature. The weight of the measure was taken and the volume of the measure was confirmed. To determine the loose unit weight of the shell, the measure was filled to overflowing with a scoop and the surface was leveled with a straightedge. The weight of the measure with the shell was taken, and then the weight of the measure alone was recorded. To determine the compact rodded unit weight, the measure was filled one-third full and leveled with the fingers. The layer was then rodded 25 times with a 5/8” diameter tamping rod evenly across the surface. This process was repeated two more times until the measure is filled to overflowing. It should be noted that when rodding each layer, the tamping rod should not be allowed to penetrate into the previous layer. After the final rodding processes, the surface was leveled with a straightedge. The weight of the measure with the shell was taken, and then the weight of the measure alone was recorded.

**Specific Gravity**

Testing for the specific gravity of crushed oyster shell was done in accordance with the ASTM C127 procedures. A random sample of shell was selected in a quartering process similar to that done in the sieve analysis and run through the
mechanical sieve machine where everything beneath the # 4 sieve was discarded. The sample, totaling 3000g, was submersed for 24 hours. After removal from the water, the sample was placed on an absorbent towel and blotted dry, only to the point that that any visible water was removed. This condition is called Saturated Surface Dry (SSD). The SSD shells were weighed and then placed into a test basket. The basket was then fully submerged in water, having taken care to remove all entrapped air that might be in the shells. The weight of the shells under water was then determined. The shells were then removed from the water and placed into a constant temperature oven to dry.

**The Ball Test**

Perhaps one of the most simple, yet important tests to determine a concrete mix's water content is called the ball test. Not to be confused with the Kelly Ball test, referenced in ASTM C360, the pervious concrete ball test requires no machines or apparatus to perform. The researcher simply attempts to form a ball with a handful of concrete. If the mix is too dry and difficult to compact and cure, the ball will crumble similar to blue cheese; too wet and the paste can slump off and the voids will close.

Very small batches were made based on a mix having a water-to-cement ratio (W/C) of 0.33 and an aggregate-to-cement ratio (A/C) of 4.0. Incremental additions of sand and water were made to the initial mix and the ball test was performed with each small batch. Several batches were also made with varying gradations of shell sizes. The final mix design, dubbed “Mix 8” is found in Table 3-1.

<table>
<thead>
<tr>
<th>Mix 8</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water/Cement (W/C)</td>
<td>0.35</td>
</tr>
<tr>
<td>Aggregate/Cement (A/C)</td>
<td>4.0</td>
</tr>
<tr>
<td>Admixtures</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3-1. Pervious oyster shell concrete.
Mixing and Compaction Techniques

Introduction

Once a mix design was decided upon, several batches were made with different compaction techniques. Testing was performed on samples derived from batches made in three separate trials; two batches were placed in conventional waxed cardboard molds and one was placed in a 4”x4.5” mold. All batches were removed from their respective molds at appropriate times and allowed to cure in the controlled environment of the Rinker laboratory for one year. Due to uncontrollable events, not all samples were able to be run through the full course of testing. Of the one-year samples, two Standard Proctor compaction, four Modified Proctor compaction and one non-compacted samples were put under compressive testing. Three Standard Proctor compaction, four Modified Proctor and two non-compacted samples were tested for permeability. Only one Standard Proctor, three Modified Proctor and one non-compacted samples were tested in the water displacement procedure. One each of the Standard Proctor, Modified Proctor and non-compacted samples placed in the 4”x4.5” molds were tested for permeability, however only the Standard and Modified compacted samples were capped and tested for compression and none were tested for density.

One 6”x6” sample, placed with the rodded compaction technique, was made 21 days before testing. This sample was tested for compression and permeability.

A large batch of pervious oyster shell concrete was mixed seven days before testing. From this mix, three samples each using the rodded, vibrated and Standard Proctor compaction techniques were placed in 4”x8” waxed cardboard cylinders. One sample each using the vibrated and Standard Proctor compaction technique was placed in a 6”x6” waxed cardboard cylinder.
Mixing

Several mixing techniques were employed during the course of this research depending on the batch size needed for testing. For the smallest batches, a clean, dry 6"x12" plastic testing cylinder was used as the mixing container. In accordance with ASTM C192 7.1.3 for hand mixing, the shells and cement were thoroughly combined then the water was slowly added until the mass achieved a desired texture and appearance and the shells were uniformly coated. The concrete was then mixed for three minutes, allowed to rest for three minutes, then mixed for an additional two minutes.

For slightly bigger batches, a clean and dry five-gallon bucket was used as a mixing container and the same procedure listed above was followed.

For the largest batch run, a procedure devised by a Southern Illinois Civil Engineering research group studying no-fines concrete was successfully used. This batch was mixed in a 1/3 yd³ machine mixer. Prior to running the machine, the mixer was “buttered” with a small amount of water; shells were then added to the mixer along with one-third of the mixing water. The mixer was then run for five minutes. The Portland cement was added and the mixer was run for another five minutes. Finally, the remaining water was added and the mixer was run for a final five minutes. The total mixing time was 15 minutes (Ghafoori, 1995).

Compaction

Several methods were employed to derive the best means of consolidating the pervious oyster shell concrete. Compaction is necessary to form a strong bond between the paste and aggregate and also to provide a smooth surface. Because of the low water content, pervious concretes mixes must be placed and compacted very quickly.
And, unlike conventional concretes mixes, commonly used equipment such as a bullfloat may not be employed as there is very little excess water to lose. Improperly compacting the concrete could potentially cause void collapse, therefore reducing its permeability or increase its likelihood of spalling once the concrete has cured.

The most common commercial compaction techniques used to date are the vibratory screed or the weighted roller, however these methods are not able to be verified or regulated by any ASTM standard or recreated on such a small scale so they were not tested in this research.

At the onset of this research, there were no beam molds available so other means were sought to test in horizontal application. As a result, early testing was performed in simple kitchen storage containers. Later research was performed in standard 4”x8” or 6”x6” vertical waxed cardboard cylinders. These vertical molds were arguably not the best choice for this type of aggregate or concrete.

Testing performed with the kitchen storage containers used rather rudimentary means of compaction including surface skreeing and simply shaking the container as an alternate to vibration.

When using waxed cardboard cylinders, four methods were used to compact the pervious oyster shell concrete: rodding, vibration, Standard Proctor and Modified Proctor.

Test cylinders were also made that had no compaction applied. These are referred to as “non-compacted.” For these samples, the concrete was placed into the containers, screed to a level finish then covered. Non-compacted samples imitate a
real-world scenario where the concrete is just placed and raked into position, screed smooth then left to dry.

Figure 3-4. Early molding techniques.

**Rodding**

In accordance with ASTM C192 7.4.2 Methods of Consolidation, Rodding, testing cylinders 2”-5” in diameter require a rod of 3/8” in diameter, and cylinders 6” require a 5/8” rod therefore the appropriate rods were used in equal strokes of 25 per layer, for two layers. The strokes were spread uniformly over the specimen and, on the upper layer penetrated one inch into the bottom layer. After each rodded session, the sides of the cylinder were tamped 10-15 times.

It was found that the fissile nature of the oyster shell caused them to seemingly lock together with the insertion of the rod, making it very difficult to penetrate deeply into the mold and at times impossible to fully reach the lower level.

**Vibration**

In an attempt to create as close to a real-world scenario as possible, yet still maintain a standardized testing methodology, specimens were compacted on a 75-Hz
frequency external vibrator but with additional weight added on top. Larger 6”x6” molds were weighed with 8.6kgs and 4”x8” molds were weighed with 3kgs. Specimens were slightly overfilled, weighed down, and then submitted to uniform vibration until the concrete ceased to settle. At that point the concrete was screed to an even finish, covered with plastic and carefully removed from the vibrator.

Figure 3-5. Vibration of a 6”x6” sample.

**The Proctor Method**

Most commonly used by scientists for soils research but for our purposes an effective tool for achieving high density is the Proctor test. The original Proctor test, ASTM D698, uses a 4-inch diameter mold that holds 1/30th ft³ of material, and calls for compaction in three layers of 25 blows by a 5.5 lb hammer, which falls 12 inches. This has a compactive effort of 12,400 ft-lb/ft³. The "Modified Proctor" test, ASTM D1557, uses the same mold, but uses a 10 lb. hammer falling for 18 inches, with 25 blows for a compactive effort of about 56,000 ft-lb/ft³.

This procedure was followed exactly for three batches of concrete, however it was discovered that the concrete developed very distinct striations at the layers. Several samples broke along the striations with the application of hand twisting or
pulling. Therefore it was decided that samples made in the fourth and final batch would be placed in only one layer. With that exception, ASTM D698 procedures were followed.

In this final batch, the collar from a Proctor hammer measure was placed on top of a waxed cardboard cylinder. A weight or flat surface was placed upon the surface of the concrete and the Proctor hammer was applied to that surface. This method was chosen to help distribute the force of the hammer’s impact, to reduce the likelihood of localized surface compaction that seem to be common with the application of the Proctor hammer, as well as to protect the concrete from developing harsh striations, which were noted above. The collar prevented the weight and concrete from displacement.

![Image of customized Standard Proctor compaction method](image)

Figure 3-6. The customized Standard Proctor compaction method.

**Pervious Concrete Testing**

**Unit Weight for Fresh Concrete**

There is a large amount of debate in the world of concrete about the correct testing method for determining the unit weight of pervious concrete. Currently, the American Concrete Institute (ACI) requires testing using the rodding and tamping techniques for measuring density found in ASTM C138, as well as the jigging technique.
in ASTM C29. However, this requirement will soon change because of a recent amendment to standards. In October of 2008, ASTM released its C1688 Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete. The new test entails a sample measure to be filled in two layers, with each layer compacted by 20 blows of a Standard Proctor hammer. According to the managing director of research and materials engineering at the National Ready Mixed Concrete Association and chairman of ASTM Subcommittee C09.49, this new method should more accurately represent consolidation results found in the field (Palmer, 2009).

At the onset of this research, ASTM C1688 had not been released and ASTM C138 was the only available unit weight test. Therefore, for the purpose of consistency, all unit weight tests in this research were performed in accordance with ASTM C138.

To perform the unit weight test, an empty measure is weighed then filled in three layers of approximately equal volume. Each layer is rodded 25 times with a 5/8” diameter tamping rod. After rodding, the side of the measure is tapped with a rubber mallet 15 times, which releases any trapped air bubbles in the concrete. After this process is concluded, the top of the concrete is screed off with a sawing motion and the measure is weighed again.

**Water Displacement Test**

It is generally accepted that for any given mixture proportion of pervious concrete, strength and permeability are a function of the concrete’s density. The greater compaction effort, the higher the strength and lower the permeability rate (Obla, 2007).

For these reasons it is vital to test the density of the various mix designs and compaction efforts for any concrete. For the purposes of this research, a test based on the Archimedes theory of water displacement was developed.
Water was placed into a contained up to a given mark. The concrete sample was submerged in the water and the amount of water displaced was determined.

**Permeability – Constant Head**

Testing for permeability in 4”x8” samples was done using a steady stream of water from a simple water faucet. Samples were either retained or returned to waxed cardboard cylinders whose top and bottoms had been removed. Above and beneath these cylinders was placed the collar of a Proctor Method container. High-adhesive tape was wrapped several times around the two to ensure a good seal. Water was allowed to flow freely in a steady, full-head stream from approximately 5” above the sample for several minutes for conditioning. When a 1” head of water could be maintained in the collar, a collection bucket was placed underneath the sample and the amount of water collected in a given amount of time was deduced.

It must be noted that several of the samples did not maintain a 1” head of water; at times ¾”-½” could be achieved, but often none at all.

![Figure 3-7. Permeability testing. A) Waxed cardboard Cylinder sample during overhead flow permeability test. B) Sample placed in 4”x4.5” mold during overhead flow permeability test.](image)
Permeability - Falling Head Apparatus

Perhaps the most accurate way to test permeability of pervious concrete is with a falling head apparatus. Unfortunately, only three pervious oyster shell concrete samples were large enough to fit into the available machine.

To use the apparatus, 6"x6" samples are fitted into a latex membrane with a clear graduated plastic cylinder placed on top. Water is poured into the plastic cylinder and allowed to drain through the concrete specimen until it is at the same level in the graduated cylinder as it is in the drain pipe. Between the plastic cylinder and the drain pipe is a control valve. This valve is opened and the time for water to fall from a given point in the graduated cylinder to a final head is taken. The rate of permeability is found using the calculations for Darcy’s Law:

\[
\frac{d^2 L}{2 \pi \varepsilon} \times \ln \left( \frac{h_f}{h_i} \right)
\]

(3-1)

Where:
- \(d_x\) = Inside diameter of falling head tube (Length)
- \(d_y\) = Inside diameter of parameter (L)
- \(L\) = Sample length
- \(h_o\) = Initial hydraulic head in falling head tube (L)
- \(h\) = Final hydraulic head in falling head tube (L)
- \(t\) = Time it takes to change from \(h_o\) to \(h\). (Time)
Sulfur Capping

Several hours prior to testing, each of the specimens was transported to the FDOT testing facility and capped with a high strength sulfur-based capping compound. This capping procedure was performed to assure even loading across the top and bottom faces of the cylinder. The capping was done in accordance with procedures outlined in ASTM C 617.
Compression Testing

After capping, samples were subjected to compression testing. Eleven samples were tested at seven days old, one sample was tested at 21 days and seven were tested at 14 months. It must be noted that several samples broke prior to compression testing. These breaks seemed to be a direct result of the concrete being placed in layers. So as to not sacrifice any potential knowledge that could be gained from compression testing the samples, the cylinders were capped at their remaining height.

Figure 3-10. Compression testing. A) Modified Proctor sample. B) Vibrated sample.
CHAPTER 4
DATA ANALYSIS AND RESULTS

Aggregate Analysis

The fact that oyster shell would prove to act as a very different form of aggregate than limestone (the most common aggregate in pervious concrete) was first made clear when the shells were crushed. Unlike limestone, which generally breaks into fairly consistently-sized rounded, smaller rocks, oyster shells often flake, resulting in pieces retaining their original size, just smaller in depth.

It should also be noted that this flaking, fissile tendency caused the crushed shell to present in longer, flatter pieces of wider gradations, but all with similar flake-like structures. When amassed, these pieces of crushed shell were very difficult to separate and scoop for testing. The scoop would almost glide over the shells unless an opening was forced. This same interlocking-type action was later noticed in the rodded compaction technique.

Once the shells were crushed, their average gradation was found through sieve analyses. Several tests were run with and without the inclusion of sand. It was found that the crushed shells already contained a large amount of fines, which would make the concrete less permeable. Finer sieves were removed from the nest to eliminate a larger amount of smaller aggregate. It was also discovered that the average random crushed sample contained a high number of larger shells, which would cause the concrete to break apart or necessitate a higher aggregate/cement ratio. It was finally decided to keep all shells passing through the ½” sieve and reject those falling beneath the #8 sieve (-1/2 + #8). The results of the sieve analysis may be found in Appendix A.
ASTM tests for rodded compact unit weight, specific gravity, density and absorption were performed, as well as a water displacement test to confirm density and specific gravity. The results are found in Table 4-1.

<table>
<thead>
<tr>
<th>Eastern Oyster Shell</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity - dry bulk</td>
<td>3.04</td>
</tr>
<tr>
<td>Specific Gravity - SSD</td>
<td>3.17</td>
</tr>
<tr>
<td>Specific Gravity- apparent</td>
<td>3.49</td>
</tr>
<tr>
<td>Density – dry bulk (lb/ft³)</td>
<td>189.79</td>
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<tr>
<td>Density – SSD (lb/ft³)</td>
<td>197.28</td>
</tr>
<tr>
<td>Density – apparent (lb/ft³)</td>
<td>217.26</td>
</tr>
<tr>
<td>Absorption (%)</td>
<td>4.2</td>
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<tr>
<td>Unit Weight – compact (lb/ft³)</td>
<td>65.7</td>
</tr>
<tr>
<td>Void Content (%)</td>
<td>65</td>
</tr>
</tbody>
</table>

Identify a Viable Concrete Mix Design

Early Trials

The first several mix designs relied heavily on the inclusion of sand, as well as utilizing large-size shells. These mixes were also placed into plastic kitchen storage containers that were often stored outside for 24-hours covered then were uncovered or were stored outside and never covered at all. Dry samples generally presented a solid impervious bottom or were simply a solid concrete substance.

Unfortunately, research data was not very well documented except for photographic evidence. None of the early samples were ever subjected to standard ASTM testing procedures. However, knowledge was gained from these mixtures that showed the importance of a low water/cement ratio, a low aggregate/cement ratio, as well as the discretionary use of fines in pervious concrete.

The Ball Test

Incrementally adding sand and water to a basic blueprint mixture was key in finalizing the ultimate mix design. Very small batches were made based on a mix having
a water/cement ratio (W/C) of 0.33 and an aggregate cement ratio (A/C) of 4.0. The
goal was to have a ball of concrete form in the researcher's hand. If the mix was too
soupy it would fall apart and lose permeability; too dry and it would crumble. It was
found that mixtures with a complete range of shells had very good adhesion with a W/C
of 0.35 and an A/C of 4.0; however the larger shells seemed to make the ball fall apart.
The same mix was made with a more defined range of shells and the ball retained its
shape.

The basic mix was made with the inclusion of 100g of sand. This made a very
well-formed ball. However, upon drying it was found that this ball had very little
permeability. This same mix was also made with 100g of sand and the addition of 75g
of water. This mixture had a large slump and would not form a ball.

It was finally decided that the initial mix, without any addition of fines and with a
narrowed selection of shell size was the best choice for a mix design. Overall, this test
was a very good indicator of what effect small changes can have on mix designs.

Pervious Concrete Testing

Void Content

Common air-void factors for pervious concrete are listed as 15-30% (Huffman,
2005). When the pervious oyster shell concrete was tested for density, however, its air-
void ratio proved to be much higher, with a range of 26-58%. The average void ratio for
the week-old rodded compaction concrete was 48.2%, the Standard Proctor compaction
concrete was even higher at 53.9% and the vibrated compaction concrete had a void
ratio average of 51.8%. The year-old Modified Proctor compacted concrete showed
much more acceptable results with an average air-void ratio of 28.5%. While an
average cannot be taken of the year-old Standard Proctor compaction and non-
compacted concrete samples because only one sample was able to be tested, their results were 37.7% and 58.6%, respectively. A graph charting the relationship between porosity and the different compaction techniques is found in Figure 4-1.

![Figure 4-1. Relationship between porosity and compaction.](image)

Table 4-2. Specific Gravity and porosity by compaction method on samples placed in 4"x8" molds.

<table>
<thead>
<tr>
<th>Compaction Method</th>
<th>7-day Specific Gravity</th>
<th>7-day Porosity (%)</th>
<th>1-year Specific Gravity</th>
<th>1-year Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rodded 1</td>
<td>0.87</td>
<td>47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.86</td>
<td>47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.03</td>
<td>51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibrated 1</td>
<td>1.08</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.08</td>
<td>53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.09</td>
<td>52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std. Proctor 1</td>
<td>1.13</td>
<td>55</td>
<td>0.74</td>
<td>38</td>
</tr>
<tr>
<td>2</td>
<td>0.97</td>
<td>49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.15</td>
<td>57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mod. Proctor 1</td>
<td></td>
<td></td>
<td>0.5</td>
<td>31</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>0.42</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>0.44</td>
<td>29</td>
</tr>
</tbody>
</table>

**Compression**

Pervious concrete is not known for its strength in compression. According to the Web site [www.perviouspavement.org](http://www.perviouspavement.org), a holding of the American Concrete Institute, the
average range of compressive strength for pervious concrete is between 500 to 4000 psi. Pervious oyster shell concrete’s strength tested on the very low end of that spectrum. When testing the 4”x8” cylinders, the average seven-day compressive strength for the rodded compaction concrete was 445 psi. The Standard Proctor method compacted concrete broke at 453 psi and the vibration compacted concrete had a very low compressive strength of 269 psi. The one-year Modified Proctor method cylinders tested at a much stronger average of 1071 psi, though the average one-year Standard Proctor method samples broke at only 251 psi. It must be noted that there were only two Standard method cylinders tested and one was broken before testing and consequently sulfur capped at partial height. This did not seem to have much of an effect on the breaking strength. The one-year non-compacted cylinder failed at 387 psi.

The highest compressive strength results resulted from breaking the one-year Standard and Modified Proctor method concrete samples that were placed in the 4”x4.5” molds. The Standard Proctor cylinder failed at 1552 psi and the Modified Proctor broke at 1592 psi.

The 21-day-old vibration compacted concrete sample broke at 481 psi. Both the rodded and Standard Proctor method compacted concrete samples were at seven-day strengths. The rodded sample broke at 505 psi while the Standard Proctor sample had a compressive strength of 543 psi. A graph charting the relationship between compressive strength and the different compaction techniques is found in figure 4-2.
Permeability

One of the best indicators of a pervious concrete’s efficacy is its permeability. In its document “Pervious Concrete ACI 522R-06,” ACI indicates that the average drainage rate of a pervious concrete will generally fall between 2 to 18 gal/min/ft², and it also state that this rate will vary depending on the aggregate use and density of the mixture. All one-week compaction efforts resulted in drainage rates well above that mentioned by ACI. The one-year samples tested with a wide range of results, from highly permeable to almost impervious.

The average permeability of a vibration compacted 6”x6” cylinder tested with the falling head parameter apparatus was 27gal/min/ft², while the average permeability of a vibration compacted 4”x8” cylinder tested by overhead flow was 22.6 gal/min/ft². A closer similarity in averages was found with the rodded compaction samples, testing 25.7 gal/min/ft² in the 6”x6” cylinders and 24 gal/min/ft² in the 4”x8” cylinders. Standard Proctor method compaction samples showed an even average with both testing methods draining at 21 gal/min/ft² in both 6”x6” and 4”x8” cylinders.
The widest range of permeability was found in the one-year samples. The samples placed with Standard Proctor method compaction had an average permeability of 9 gal/min/ft², while those placed with the Modified Proctor method had an average of 0.5 gal/min/ft². The non-compacted samples drained conversely at an average of 21.7 gal/min/ft².

Those samples placed in the 4"x4.5" molds were tested in situ. The Standard Proctor compaction method sample had a drainage rate of 7.3 gal/min/ft², while the Modified Proctor compaction method sample drained at 2 gal/min/ft² and the non-compacted sample at 18.9 gal/min/ft².

![Figure 4-3. Relationship between permeability and compaction.](image)

**Table 4-3. Compressive strengths and permeability rates of one-year samples in 4"x4.5" molds.**

<table>
<thead>
<tr>
<th>Compaction Method</th>
<th>Compressive Strength (psi)</th>
<th>Permeability (gal/min/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std. Proctor</td>
<td>1552</td>
<td>7</td>
</tr>
<tr>
<td>Mod. Proctor</td>
<td>1596</td>
<td>2</td>
</tr>
<tr>
<td>Non-Compacted</td>
<td>N/A</td>
<td>19</td>
</tr>
</tbody>
</table>
Table 4-4. Compressive strengths and permeability rates of 7-day and 21-day samples placed in 6”x6” molds.

<table>
<thead>
<tr>
<th>Compaction Method</th>
<th>7-day Compressive Strength (psi)</th>
<th>7-day Permeability (gal/min/ft²)</th>
<th>21-day Compressive Strength (psi)</th>
<th>21-day Permeability (gal/min/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rodded</td>
<td>505</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Custom Std. Proctor</td>
<td>543</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibrated</td>
<td></td>
<td></td>
<td>481</td>
<td>27</td>
</tr>
</tbody>
</table>

Table 4-5. Compressive strengths and permeability rates of 7-day and 1-year samples placed in 4”x8” molds.

<table>
<thead>
<tr>
<th>Compaction Method</th>
<th>7-day Compressive Strength (psi)</th>
<th>7-day Permeability (gal/min/ft²)</th>
<th>1-year Compressive Strength (psi)</th>
<th>1-year Permeability (gal/min/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rodded 1</td>
<td>460</td>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>516</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>360</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std. Proctor 1</td>
<td>442</td>
<td>21</td>
<td>297</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>466</td>
<td>20</td>
<td>205</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>451</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibrated</td>
<td>N/A</td>
<td>23</td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td>206</td>
<td>22</td>
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<tr>
<td>3</td>
<td>329</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified Proctor 1</td>
<td></td>
<td></td>
<td>920</td>
<td>0.3</td>
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<td>2</td>
<td></td>
<td></td>
<td>1291</td>
<td>0.3</td>
</tr>
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<td>3</td>
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</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>978</td>
<td>N/A</td>
</tr>
<tr>
<td>Non-Compacted</td>
<td></td>
<td></td>
<td>378</td>
<td>21</td>
</tr>
</tbody>
</table>
CHAPTER 5
SUMMARY AND CONCLUSION

The purpose of this research was to develop a pervious concrete using recycled oyster shells as the aggregate. To accomplish this, the following tasks were performed:

- Eastern Oysters shells were collected, cleaned and crushed, then their properties analyzed for particle size, specific gravity, density, absorption and unit weight.
- A pervious oyster shell concrete mix was designed using trial batches and the ball test.
- The pervious oyster shell concrete was placed with three compaction techniques then tested for unit weight, density, permeability and compression.

It was found that a pervious oyster shell concrete could be designed, however it was also discovered that the process of acquisition and cleaning of the shells may prove too labor intensive to make the mix viable on a large scale. There were also complications in the test methods implemented in this research that might have led to a weakness in the overall data.

Complications

There was some inconsistency in data acquisition.

- Some samples were not included in a few of the tests so broad scope conclusions couldn’t be drawn.
- A larger quantity of samples should have been made so a better scientific data set could be taken.

Based on the research, several assertions may be concluded regarding the pervious oyster shell concrete, as well as the oyster shell as an aggregate.

Conclusions

It may be assumed that with the proper compaction technique, the oyster shell will be proven to be a very strong aggregate. This presumption is based on the locking tendency of the aggregate shell that was observed in the rodding compaction technique.
as well as when the shell was amassed. The validity of this assumption needs to be established with further research.

The conclusion may be drawn that pervious oyster shell concrete should be limited to outside use, as a faint odor persists around the material even after curing for one year. This issue may be resolved if the shells were superheated or cleaned with other methods, however that is a topic that would need to be validated with additional research.

Recommendations for future research:

- Place pervious oyster shell concrete into large panels and compact with several different techniques, namely a weighted roller and vibrating roller.
- Test pervious oyster shell concrete for permeability while in the above-mentioned panels. Several methods for in-situ testing are currently being developed for standardization and are available for acquisition via the Internet.
- Develop additional mix designs that incorporate recycled content such as blast furnace slag or fly ash, to further increase not only the physical properties of the concrete, but also the sustainable attributes as well.
- Develop additional mix designs that incorporate different gradations of shell aggregate in order to potentially provide better compaction ratings.
Figure A-1. Results of test using sieve sizes 1½"-#30.
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BIOGRAPHICAL SKETCH

Kristy Noel Kelley is an eighth generation North Floridian born in Tallahassee in 1974. She is an alumna of Tallahassee Community College where she took an Associate in Arts and graduated Cum Laude, and Florida State University, where she took a degree in English with a minor in history. After working several years as a writer with the Tallahassee Democrat, she worked for the Tallahassee Trust for Historic Preservation (TTHP). It was working for the TTHP that she began to see her plan for working with historic buildings unfold. Kelley worked as a laborer for a short time for Lambert Construction Company in Tallahassee. It was there that her life changed, discovering the fragility of bones and ligaments. She entered the M.E. Rinker, Sr. School of Building Construction in August of 2004 and has pursued her graduate degree despite many setbacks and frustrations, with the support of her incredible family. She will graduate on her 35th birthday in December of 2009.