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WASTE CLAY AS A GREEN BUILDING MATERIAL

FINAL REPORT

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FINAL REPORT

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PERSPECTIVE

Patrick Zhang, Research Director - Beneficiation & Mining

The Florida phosphate industry produces tens of millions of tons of phosphatic clays and flotation tailings each year. The clay and sand components in these by-products have been used as building materials since ancient history. Rammed earth has been used in China for nearly three thousand years, with a multi-story, half-million square feet structure holding steady for 500 years. This technology was also used in England, Russia and Spain to build churches, homes and castles. Many of the centuries-old landmarks built with rammed earth still hold firmly. In a similar process earth is compressed into blocks, which are then used in the same way as conventional masonry units to build walls.

Since both rammed earth and the compressed blocks use natural earth materials with a small amount of binders, they are gaining popularity as "green" building materials. This research investigated the potential use of waste clay and tailing sand from the phosphate beneficiation process as the primary ingredients in rammed earth and compressed earth blocks for commercial and residential construction projects.

Generally, rammed earth is consisted of 30% clay and 70% sand. In ancient times, the compaction and cementation of rammed earth were accomplished by the clay component; in modern times a small amount of Portland cement is used to meet construction codes. Another application of compressed earth as a building material is compressed earth bricks. This type of building material is considered "green" because it consumes much less energy to make than other material. For example, compressed earth brick production uses about 25% of the total energy per unit needed to produce an ordinary clay brick.

This project produced mixed results. The positives include successful manufacturing of compressed clay/sand blocks and high strength of the blocks. However, the blocks failed to meet two elements of the Florida Building Code: water absorption rate and radon emission. The Florida radon standards for new construction are voluntary, but may be adopted as a requirement by local jurisdictions. More research and testing are necessary to address these two issues.

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We would like to thank the Florida Institute of Phosphate Research for its financial support and assistance and CF Industries for providing samples of waste clay. Compression tests were performed at the University of South Florida Structures Lab by Danny Winters. Absorption and leaching tests were performed at the University of South Florida Department of Civil and Environmental Engineering by Dr. Maya Trotz and assistant Andrew Tankel. Radiation tests were performed at the University of Florida Nuclear and Radiological Engineering Lab by Mark J. Harrison, Ph.D.

ABSTRACT

Two of the primary waste components of the phosphate beneficiation process, sand and clay, have been used as building materials for thousands of years. A process known as rammed earth has been used extensively around the world in buildings that have lasted for centuries. Because earth is the main ingredient in rammed earth it has recently enjoyed new popularity as a so called “green” building material. In a similar process earth is compressed into blocks which are then used in the same way as conventional masonry units to build walls. In the compressed earth block (CEB) method, individual units can be manufactured and stockpiled for later use rather than being fabricated on site as in the rammed earth process. This research project will investigate the potential use of waste clay and tailing sand from the phosphate beneficiation process as the primary ingredients in compressed earth blocks for commercial and residential construction projects.

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EXECUTIVE SUMMARY

The goal of this project was to assess the technical and economic viability of making block for the construction industry using waste clay from Florida's phosphate benefaction process together with other recycled materials and stabilizers.

The research began with the identification and acquisition of materials. The age old processes of rammed earth and compressed earth block (CEB) were used as precedents because of their low embodied energy and small carbon footprint when compared to conventional cement masonry units or clay fired bricks. Rammed Earth and compressed earth block both contain roughly 70% sand and 30% clay. Waste clay and tailing sand were acquired from CF Industries in Bowling Green, Florida. Tailing sand is extremely fine grain and to facilitate good compaction we mixed it with medium and course sand. We also used filtered crushed recycled concrete as an aggregate. Portland cement, recycled fly ash and lime were used as stabilizing agents and to add strength to the blocks.

Dry ingredients were mixed in a cement mixer and placed in a plastic mortar box to be mixed with the wet waste clay. Several different mixtures varying the percentage of each material were tried in order to find the strongest, most economical mixture with the highest possible recycled content. After the materials were mixed they were placed into a MP612 compressed earth block press manufactured by Fernco Metals. The press makes one 6” × 12” × 4” block at a time. After compacting the materials into a block in the press, the blocks were removed and placed on a shelf and allowed to cure for 28 days before any testing was done.

After 28 days had passed, the blocks were taken to the USF College of Engineering's Structural Testing Lab and tested for compressive strength. The Florida Building Code standards for adobe construction were used as the criteria for evaluation of the strength of the blocks. The FBC requires adobe to have a compressive strength of 300 psi or more. From the compressive strength tests 2 mixtures were chosen for additional testing based on strength, economy, and the amount of recycled content. Economy was based on the amount and kind of stabilizer added to the mix as the stabilizer tends to be the highest priced element.

Samples of the two block mixtures were taken to the USF Department of Civil and Environmental Engineering for absorption and leaching tests. Samples were also taken to the University of Florida Nuclear and Radiological Engineering Lab for radiation testing. Although several samples were found to be strong enough in compression, the results of further testing revealed that their absorption rate was higher than that allowed by the FBC and the rate of radon emission exceeded U.S. clean air standards.

A full discussion of the work is given below.

INTRODUCTION

The mining and beneficiation of phosphate rock produces large quantities of phosphatic clays. Approximately one ton of clay is generated for each ton of phosphate rock product. Nearly 100,000 tons per day of waste clays are currently produced by the phosphate mines in Florida. The waste clays create one of the most difficult disposal problems in the mining industry. The standard disposal method requires constructing huge settling ponds, using a great amount of water and large acreages of land which otherwise could be used for agriculture, construction or recreation. As of November 30, 1994, 84,218 acres of unreclaimed clay settling areas had accumulated in central Florida. The phosphates industry currently leaves 40% of its mined land as clay settling areas. According to the website of the Florida Institute of Phosphate Research (FIPR), http://www.fipr.state.fl.us, there are some potential uses for this land, but because of its general instability, concerns about radioactivity of the area and the presence of radon gas, these uses are very limited. There is a public demand to reduce the area devoted to clay settling and there has been considerable research done on the rapid dewatering of waste clay and commercial uses for the clay once it has been dewatered. FIPR grants have supported several projects aimed at finding uses for phosphatic clay, e.g., final reports by Boyd and others (2007) and El-Shall (2007).

Two of the primary waste components of the phosphate beneficiation process, sand and clay, have been used as building materials for thousands of years. In one particularly noteworthy case, a process known as rammed earth has been used extensively around the world in buildings that have lasted for centuries. Because actual earth is the main ingredient in rammed earth, it has recently enjoyed new popularity as a so called “green” building material. In a similar process, earth is compressed into blocks which are then used in the same way as conventional masonry units to build walls. In the compressed earth block method, individual units can be manufactured and stockpiled for later use rather than placing the raw material directly in formwork at the site, as in the rammed earth process.

In China, rammed earth has been used since the third millennium B.C. and is still being used today. In Tongding County, large multi-story rammed earth buildings up to 538,200 sq. ft. in size exist, some of which have been standing for 500 years. Although often hard to identify because of the plaster coating hiding the earth construction, rammed earth churches, homes and castles occur in England, Russia and Spain. Part of the palace of Versailles in France is earth-walled (Baggs and Baggs 1997). In the U.S., Spaniards constructed the first permanent structures in St. Augustine, Florida, in the mid-16th century using a mix of soil and shells rammed into a heavy wooden framework. One of those original buildings still stands today (Pearson 1998). An ideal soil for rammed earth is one in which the colloidal cementation supplements thorough compaction. Colloids are a sort of natural gelatin found in clay soils. Ramming earth massages the colloids into action in much the same way that kneading bread dough works up the gluten in flour. Compaction and cementation have proven successful in all of the world’s ancient rammed earth structures. Modern building codes may require that earth be stabilized when it is used as a building material. According to Easton (2007), in reference to rammed earth construction, "Stabilization is the elimination of the change in volume that occurs in a soil as it absorbs and discharges water." Portland cement, a stabilizing agent used in making rammed earth, both reduces absorption and increases strength. Hydrated lime reacts chemically with clay to alter its expansiveness, which in turn improves its natural stability. Most of the world's oldest rammed earth walls were constructed with basically the same soil composition—roughly 70% sand and 30% clay (Easton 1996). Another application of compressed earth as a building material is compressed earth bricks (CEB), which are made up of clay sand and loam milled and mixed with cement. Compressed earth-brick production uses approximately 25% of the total energy per kilogram needed to produce an ordinary clay brick, 35% of that necessary to produce a concrete block, and 20-35% of that necessary to produce sawn softwood and hardwood (Baggs and Baggs 1997).

Stein and Reynolds (2000) give the following list of embodied energy of some common building materials in btu/lb.:

Stabilized adobe	123
Fired brick	4000
Concrete block	730-960
Portland cement	2400-4000
Steel framing	19,200

The compressed earth block technique is an improvement of the adobe technique, where blocks are created by forming earth into wooden formwork by hand. The CEB process involves the use of a steel press that compresses the blocks by mechanical or hydraulic power. The CEB is more regular in size and shape, and it is much denser than the adobe block. As a result, it has better resistance to water and compressive stresses. The basic earth mixture consists mainly of sand, clay, and small gravel. In addition, stabilizers, such as Portland cement or lime, can be added to increase the compressive strength of the block, and the mixture can contain fine aggregates, silts, ashes or natural fibers.

The Florida Building Code accepts adobe as a building technique, where earth is molded into a brick form, and then dried in the sun. For the use of compressed earth blocks, where the earth is compressed into blocks via mechanical or hydraulic press, the same code restrictions apply as those for adobe.

This project focused on using waste materials of the phosphate mining process (tailing sand and phosphatic clay) together with stabilizing agents to make an economical material for rammed earth and compressed earth brick construction.

IMPACTS

- The use of waste materials from phosphate mining as construction materials would provide a useful, economically viable and environmentally sound alternative to the waste clay retention ponds currently in use.

- The low embodied energy of walls and bricks made from recycled waste materials would reduce the carbon footprint of the construction industry.
- Sister industries to the phosphate industry would provide local economic stimulus.
- The conversion of waste materials to environmentally friendly building materials and the subsequent reduction in the need for retention ponds, would improve the image of the phosphate industry in the eyes of the community.

BENEFITS TO THE STATE OF FLORIDA

- The State would benefit from a reduction in the amount of valuable land dedicated to clay settling ponds.
- The image of Florida as an environmentally conscious state would be enhanced by the introduction of an innovative and environmentally friendly use for waste materials.
- A sister industry to the phosphate industry that manufactures construction materials would generate new jobs and investment in the state and reduce the burden on other raw materials for construction.

METHODOLOGY

GENERAL PLAN OF WORK

Various mixtures of sand, gravel, dewatered clay, lime and cement and other admixtures were formed into compressed earth blocks (CEBs). The blocks were then tested for code compliance concerning moisture content, shrinkage cracks, absorption characteristics, compression and modulus of elasticity.

EQUIPMENT

The MP612, produced by Fernco Metals, is a portable, manually-operated press that produces a 6" × 12" × 4" block which is moderately light in weight and easy to handle. High-quality steel construction and grease fittings at all critical locations ensure smooth operation and long life with a minimum of maintenance. The two 6-foot rails provide stability during operation and can be detached before transport, as can the two-piece 6-foot compression handle. The optional wheel kit makes it easy to move at the building site. The press is painted Safety Yellow for high visibility and to prevent rust.

Figure 1. Fernco Metals MP612 Portable Press.

MATERIAL IDENTIFICATION AND SOURCING

There are many variables in the design of the earth mixture. The clay content for CEBs can vary from 10-40% of the mixture, depending on the type of clay and other materials used. The different types and sizes of sand, silt and gravel also play a large role in the final strength of the block. However, one of the most important factors of the mix is a good grain size distribution. The main technique in the fabrication of the block is compression, so the mix has to be designed in a way that the particles of the clay and the sand can compact to a dense mass and form a strong bond, leaving little almost no air gaps. In addition, the mix had to be combined well, so that the clay can adhere to all particles in the mix.

The initial phase of the project included the investigation and sourcing of material components, local sources, recycled components, additives, and stabilizers. The main focus was to create a CEB containing local phosphatic clay that is strong enough to meet the requirements of the Florida Building Code (Florida Building Commission 2008). The goal was to produce a strong CEB that makes use of as many local, recycled, and sustainably acquired materials as possible.

Clay

Clay was collected from the settling ponds of CF Industries in Bowling Green, Florida. Two types of clay were collected. The first type of clay was pumped directly from the bottom of the settling pond via a large centrifugal pump. This clay contained a high percentage of water and had a slurry consistency. It was, however, free of any other natural fibers or impurities.

(a) (b)

Figure 2. Views of CF Industries Centrifugal Pump.

The second type of clay was shoveled by hand from a reclaimed area, where the clay had been settling for approximately eight years. The clay was much drier and denser and contained natural fibers and other plant materials mixed with the clay.

Figure 3. CF Industries Reclaimed Field.

Sand

For a good grain size distribution, different sizes of material components are preferred. The sand with the smallest grain size, tailing sand, is a byproduct of the beneficiation process and was collected from CF Industries.

(a) (b)

Figure 4. CF Industries Tailing Sand.

The medium-sized sand commonly known as *construction sand* or *sand box sand* was purchased through a local building supply store.

Figure 5. Medium Sand.

The coarse sand, also known as well point sand, was obtained from a local sand and gravel supplier.

Figure 6. Coarse Sand.

Crushed Concrete

The recycled product, crushed concrete (CC), was used as part of the sand mixture, and it was acquired from Kimmins Contracting Corp., a local company that crushes concrete salvaged from building demolitions, etc. The concrete is passed through a crushing machine, where the reinforcing steel is separated from the rest of the material.

The crushed concrete pieces are sifted, and crushed again, if necessary. The material is also known as *road base*, and it is used in highway construction. The final CC product is a mixture of fine, medium and large pieces of aggregate, concrete, and sand. The material was used in its original state (containing gravel up to 1” in size) and was also filtered through a ¼” sifting device to isolate the smaller aggregate.


(a) **(b)**

Figure 7. Crushed Concrete.


(a) **(b)**

Figure 8. Sifting Crushed Concrete.

Fly Ash (Class F)

Fly ash is a fine residue resulting from the combustion of ground or powdered coal. The particles are generally finer than Portland cement. There are two different types of fly ash currently produced in the USA that are specified in ASTM C 618: Class F and Class C. Class F is fly ash normally produced from burning anthracite or bituminous coal, and Class C is normally produced from the burning of sub bituminous coal and lignite. Class C fly ash has cementitious properties in addition to pozzolanic properties due to free lime, whereas Class F is only cementitious when mixed with water and another agent, such as Portland cement, lime or other chemical activators (ASTM 2003).

Figure 9. TECO "Big Bend" Power Plant.

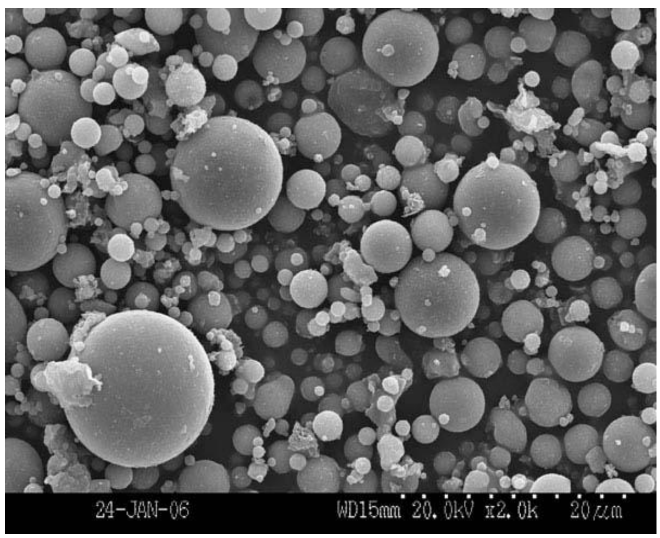

Figure 10. Microscopic View of Fly Ash.

For this project, we used Class F Fly Ash, produced by the local TECO "Big Bend" power plant in Apollo Beach, FL, and then purified by the local company, Separation Technologies LLC. Initially, the fly ash was intended as a stabilizer to replace some of the Portland cement in the mix; however, after using the material in connection with the CEB process, other beneficial characteristics were discovered. The addition of fly ash increased the workability of the mix. In addition, the blocks seemed to compress easier and denser, and the final blocks looked smoother than the blocks without the fly ash. It also changed the color of the blocks from a light brown tone to a dark gray color.

Lime

Free lime or garden lime was used as a stabilizer to regulate water content and facilitate the tight compression of materials.

Portland Cement (PC)

Portland cement (PC) was used as a stabilizer and to give the material the strength necessary to meet code requirements. All else being equal, the compressive strength of the block samples was directly proportional to the percentage of PC in the mix. Commercial cement masonry units (CMUs) contain 10% Portland cement by weight (PCA 2011a). The manufacture of cement produces about 0.9 pounds of CO_2 for every pound of cement (PCA 2011b). In addition, PC has a relatively high embodied energy so every effort was made to use as little as possible in the CEB mixes. Six percent PC by weight (7% by volume) was enough to provide the CEB with enough strength to satisfy the building code while using only 60% of the quantity typically used in CMU, thus significantly reducing the carbon footprint and the embodied energy of the CEB.

BLOCK FABRICATION

Mixing

The materials were mixed in different combinations and proportions in an attempt to find the strongest, most economical mix. Recycled content was a high priority and many different combinations and proportions of natural, manufactured and recycled materials were tested as outlined in Table 1. An effort was made to keep a consistent and accurate mixing process throughout the project. First, the dry components (sand, crushed concrete, fly ash, cement, lime) were placed in a concrete mixer and mixed for several minutes. The dry mix was emptied into a mortar box where the clay was added. For the purpose of these experiments the clay in a slurry state was easier to handle than the dryer clay because it mixed uniformly with the sand whereas the dry clay remained in clumps and did not mix well with the aggregates. It was difficult to maintain a consistent water/solid ratio in the slurry clay, which led to some inconsistencies in the material mixes. If dry clay could be pulverized into a powder form, mixed with the other dry ingredients and then a consistent, measured amount of water added, the results would be more consistent and uniform. Given the limitations of using clay in its slurry form, the best way to test the moisture content of the mix was to take a small amount in hand and press it into a ball. The ball should keep its shape when in hand, but break into small pieces when dropped on the ground.

Figure 11. Mixing Materials in Mortar Box.

Sixteen different mixtures of materials in various proportions were made into blocks, as shown in Table 1.

Table 1. Test Mixtures (%) by Volume.

Date	Mix	Clay	Crushed Concrete	Fly Ash	Cement	Fine Sand	Medium Sand	Coarse Sand	Lime
2/12/10	1	20	20			20	20	20	
2/15/10	2	30	20			16.7	16.7	16.7	
2/15/10	3	20	20	20		20		20	
2/25/10	4	20	19	19	4	19		19	
2/25/10	5	20	17.5	17.5	10	17.5		17.5	
2/26/10	6	20	18.25		7	18.25	18.25	18.25	
2/26/10	7	30	18.25		7	14.92	14.92	14.92	
3/18/10	8	23	20	3.5	3.5	16.7	16.7	16.7	
3/18/10	9	23	20	7		16.7	16.7	16.7	
3/19/10	10	23	20	3.5		16.7	16.7	16.7	3.5
3/19/10	11	23	70	7					
5/14/10	12	20	63	10	7				
5/27/10	13	20		20	7	26.5		26.5	
5/27/10	14	20		15	7	29		29	
6/1/10	15	20		10	7	31.5		31.5	
6/1/10	16	20	53	20	7	26.5		26.5	

Shaded rows indicate the mixtures chosen for additional testing.

Workability Factors

As mentioned, the slurry clay that was pumped from the pond was the preferred clay to use. It had a dependable consistency, and it was free from any other impurities. It was hard, however, to obtain a stable water amount in the clay after storing it for several days, so a different process should be considered. For example, if dry clay could be pulverized into a powder form, mixed with the other dry ingredients and then a consistent, measured amount of water added, the results would be more consistent and uniform.

The addition of fly ash (in this first test phase 20% of the mixture) increased the workability of the mix. In addition, the blocks seemed to compress easier and denser, and the final blocks looked smoother than the blocks without the fly ash. The later blocks were more sandy and grainy in texture, whereas the blocks containing the fly ash had a finer grain structure. The fly ash also changed the color of the blocks from a light brown tone to a dark gray color.

Compaction

Once the materials were mixed and had the right moisture content, the mixture was poured into the chamber of the MP612 compressed earth block press manufactured by Fernco Metals, the lid closed, and pressure applied via the long steel lever. The press makes one 6” × 12” × 4” block at a time.

Figure 12. Adding Loose Material to Press.

Figure 13. Compacted Material in Press.

Figure 14. Operating Block Press.

Curing

The 12” × 6” × 4” blocks were taken from the press and moved to shelves where they were labeled according to mixture and date and allowed to cure. As Portland cement was used as a stabilizer and 28 days is the standard for letting concrete cure before compression tests are performed, the CEB were allowed to cure for the same 28 days. Portland cement gains strength through hydration and strength can be optimized by slowing the evaporation of moisture from the surface of the blocks during the curing period. This is particularly important with CEB as very little water is added and the mix is relatively dry at the time of compaction. To limit evaporation and facilitate complete hydration of the Portland cement, blocks were wrapped in plastic for the entire 28-day cuing period. For blocks that do not include PC as a stabilizer, the curing time and method should be adjusted accordingly.

(a) (b) (c)

Figure 15. Removing CEBs from Press.

Figure 16. CEBs Curing.

TESTING

After curing for 28 days, the blocks were subjected to a series of tests to determine their compliance or non-compliance with the FBC and to see if they posed any potential health or environmental risks. Strength was identified as a prerequisite for further testing so all 16 of the mixes were tested in compression. Two mixes (Numbers 12 and 15 in Table 1) were selected for further testing based on their strength, economy, and recycled content. Economy was defined as a minimal use of Portland cement, lime and other processed stabilizers that would add cost to the CEB.

Compressive Strength Testing

Compression tests were performed by Danny Winters, the manager of the USF Department of Civil and Environmental Engineering Structural Testing Lab. The lab is equipped with a static, PC-controlled, axial test system for measuring the compressive and tensile strength of materials. The blocks were placed flat in the testing device, and compressed until failure occurred. Table 2 includes the results of the testing done on samples from all 16 mixes. Of the 16 different mixes tested, 9 were found to have a compressive strength at or above the FBC requirement of 350 psi for single-story adobe structures.

Figure 17. Compression Testing.

Table 2. Compression Test Results (PSI).

Test Date	Mix No.	Comments	Test 1 (PSI)	Test 2	Test 3	Avg. PSI
3/25/2010	1		52.4			52.4
3/25/2010	2		60			60
3/25/2010	3		99	174		136.5
3/25/2010	4		702	1238	830	923.5
3/25/2010	5		962	814		888
3/25/2010	6		444.8	444		444.4
3/25/2010	7		508	524		516
4/28/2010	8		296	339		317.5
4/28/2010	9		118	70.5		94.25
4/28/2010	10		106	113		109.5
4/28/2010	11		195	200		197.5
6/30/2010	12		591	588		589.5
6/30/2010	13		497	375		436
6/30/2010	14		464	481		472.5
6/30/2010	15		580	632		606
6/30/2010	16		494	415		454.5

Note: Shaded rows indicate the mixtures chosen for additional testing.

MOISTURE ABSORPTION TESTS

The purpose of the test was to investigate the elemental leaching and absorption behavior of five 4 × 4 cubes and the amount of moisture absorbed based on criteria listed in FBC 2109.8.2.1.2. According to the FBC, absorption tests should be conducted after 28 days of brick manufacture. Four-inch (102 mm) cubes, cut from a stabilized adobe unit, must be dried to a constant weight in a ventilated oven at 212°F to 239°F (100°C to 115°C) and then be placed upon a constantly water-saturated, porous surface for seven days. A minimum of five specimens should be tested with each specimen cut from a separate unit. Ideally the block must absorb no more than 2.5% moisture by weight. Twelve four-inch cubes were obtained from Professor Russell and these were used for absorption and then leaching studies.

Given that the building code does not explicitly state the porous surface or conditions to use for this test, two scenarios were created. One involved the blocks placed on a sponge and the other involved the blocks placed in a water solution. For this test, six cubes (Numbers 1-6) were placed in an oven at 105°C for two days to achieve a constant dry weight. Once this was achieved, they were placed upon individual wet sponges for seven days at room temperature. The sponges required constant re-soaking and this can be attributed to the moisture being absorbed into the cube, as well as evaporative losses.

The remaining six cubes (Numbers 7-12) were placed in an oven at 105°C for a total of three days to ensure constant dry weight and then placed in groups of two in a plastic tub that had no greater than 1” of water at all times inside it. This lasted for seven days as well. The water inside the tub did not disappear as quickly as experienced with the sponge testing. An analytical balance was used to record all weights in grams. The formula used to arrive at the final percent change was:

*[(Initial Weight-Final Weight)/(Initial Weight)]*100*

Table 3 summarizes the absorption data of the twelve different bricks, six of which were exposed to a wet sponge surface and six of which were placed in 1” of water in a plastic tub. The water absorbed for all twelve of the bricks was between 16.4 and 22% of the initial weight of the brick and averaged 18.8%, with a standard deviation of 1.5%. These values are above the building code requirements.

Table 3. Absorption Test Results.

Blocks Sitting on Wet Sponges				Blocks Sitting in 1 Inch of Water			
Block:	Initial Wt. (g)	Final Wt. (g)	% Change in Wt. Due to Absorption	Block:	Initial Wt. (g)	Final Wt. (g)	% Change in Wt. Due to Absorption
1	1758.95	2101.78	19.5	7	1732.35	2072.22	19.6
2	1750.98	2037.84	16.4	8	1508.54	1781.92	18.1
3	1646.82	1943.36	18.0	9	1422.8	1735.96	22.0
4	1701.54	2041.92	20.0	10	1721.41	2044.49	18.8
5	1700.70	2022.6	18.9	11	1750.76	2046.93	16.9
6	1619.85	1914.8	18.2	12	1491.32	1779.38	19.3
Average (%)			*18.5*				*19.1*
Standard Deviation (%)			*1.3*				*1.7*
Average, on Sponges & in Water (%)					*18.8*		
Average Standard Deviation, on Sponges & in Water (%)					*1.5*		

ELEMENTAL LEACHING BEHAVIOR TESTS

Five of the blocks (Numbers 1, 3, 5, 7, and 10) that had previously been exposed to the absorption test were selected for the leaching study. Using a hammer, a sample of each block was removed and crushed by a pestle in a porcelain mortar. One gram of each crushed sample was placed in a clean 1 L Pyrex beaker along with 1 L of deionized water. The solutions were stirred using a Teflon stirrer, but this was not done continuously. The crushed sample, if anything, would represent the higher end of leached metals expected since more surface area is exposed. Samples (40 mL) were removed on Oct. 14, 15, 17, 19, and 27, 2010. The samples were placed in an Environmental Express sample tube and filtered. No precautions were taken to limit evaporative losses from the beakers except covering them with parafilm. The filtrate was analyzed on ICP-MS by Dr. Zachary Atlas, who is an Associate Research Scientist for the University of South Florida’s Geology Department. Elements tested were: Na, Mg, Al, K, Ca, Mn, Fe, Ba, Cu, Pb, Hg, Ni, P, Sr, Zn, Cd, Ce, Se, Mo, Si. Table 4 summarizes the results from the leaching tests and Tables 5-9 provide the detailed leaching results for each brick (Table 4 lists the average of the amount leached based on the data presented in Tables 5-9). The final samples had very high concentrations of calcium (Ca) and sodium (Na), while having little to no concentration of lead (Pb) and mercury (Hg). Additionally, higher concentrations of copper (Cu), molybdenum (Mo), nickel (Ni) and zinc (Zn) were found.

Table 4. Leaching Test Results (μg/L) Compared with EPA Recommended Water Quality Criteria.

Element	Average	National Standard (Fresh Water)
Sodium	8093.42	NL*
Magnesium	3360.07	NL
Aluminum	0.50	87
Potassium	1141.07	NL
Calcium	106132.66	NL
Manganese	8.63	NL
Iron	4.48	1000
Barium	16.62	NL
Copper	88.84	NL
Lead	0.00	2.5
Mercury	-0.02	.77
Nickel	5.31	52
Phosphorus	42.93	NL
Strontium	279.27	NL
Zinc	24.78	120
Cadmium	0.60	.25
Cerium	0.00	NL
Selenium	2.11	5
Molybdenum	82.44	NL
Silicon	3696.75	NL

Note: *NL- Not listed by EPA in National Recommended Water Quality Criteria (USEPA 2009).
▒ Potential environmental hazard.

RADIATION TESTS

Based on tests performed by Dr. Mark J. Harrison at the University of Florida Department of Nuclear and Radiological Engineering, brick samples were determined to be slightly above the minimum detectable activity (MDA) level and there was no statistically significant variation in alpha particle count between samples from the two different mixes. To put the findings in perspective, the brick samples were compared to clay-based kitty litter as a common household material containing a low level of radiation. No statistically significant difference was found between the brick samples and the kitty litter.

Gamma-ray measurements were performed on the brick samples to detect the presence of radon. To determine the activity of Bi-214 in the blocks, each block was ground into a powder form and set to count for 24 hours in a low-background high-purity germanium (HPGe) gamma-ray spectrometer. Each sample clearly produced gamma-ray peaks at 609.3, 768.4, 934.2, 1120.6 and 1238.5keV, all indicative peaks of Bi-214 (Figure 17). The test samples were found to have an average volumetric decay rate of Bi-214 of 50.4 ± 12.1 kBq/m^3. Since Bi-214 is a daughter to Rn-222 and the decay chain is assumed to be in equilibrium (i.e., the production and destruction of all members is equal), the production rate of Rn-222 (radon gas) was also assumed to be 50.4 ± 12.1 kBq/m^3 (Table 5).

To understand these findings relative to radon standards for building interiors in the U.S., the radon concentration was calculated in a hypothetical room measuring 3 meters square in plan with 3 meter high walls made of the test blocks. Assuming that 10% of the radon produced by the material would be emitted to the interior space, it was determined that the space would have a radon level of approximately 533 Bq/m^3 (UNSCEAR 1982). The EPA considers 120 Bq/m^3 to be an elevated level so a building made of the blocks would clearly exceed current clean air standards for radon concentration (USEPA 2011). In conventional construction practices in the U.S., the interior surface of the block wall would be covered with a vapor barrier, insulation, wall framing and gypsum board, presumably reducing the amount of radon emitted to the interior of the building. Sealers applied to the surfaces of the blocks might also result in reduced radon emissions. The method of testing samples in a powder form might have yielded higher emission rates than if the blocks had been tested in their solid form. Additional research is necessary to determine the actual radon emission rate of the blocks in their solid form and how finish materials or sealers on the inside of the blocks would affect the radon concentration in a room.

Table 5. Radiation Test Results.

	Energy	Gross Cts. (cts/day)	Bkgd. Cts (cts/day)	Net Cts		Abs. FEP Efficiency			Absolute Yield	Bi-214 Activity	
				Avg. (cps)	Error (cps)	Avg. Efficiency	% Err. sigeff	Err.		Avg. (Bq)	Err. (Bq)
A	609.3	31700	1810	0.346	0.00212	1.03E-02	1.59%	1.64E-04	0.4611	72.83	1.54
	768.42	2910	117	0.032	0.00064	9.47E-03	1.83%	1.73E-04	0.0494	69.05	3.45
	934.23	1360	50	0.015	0.00043	8.75E-03	1.99%	1.74E-04	0.0303	57.16	3.98
	1120.58	4930	266	0.054	0.00083	7.78E-03	2.24%	1.74E-04	0.1510	45.97	1.56
	1238.55	1720	76	0.019	0.00049	7.53E-04	2.34%	1.76E-05	0.5791	43.62	2.31
B	609.3	30100	1810	0.327	0.00207	1.03E-02	1.59%	1.64E-04	0.4611	68.93	1.39
	768.35	2680	117	0.030	0.00061	9.47E-03	1.83%	1.73E-04	0.0494	63.36	3.05
	934.12	1230	50	0.014	0.00041	8.75E-03	1.99%	1.74E-04	0.0303	51.48	3.49
	1120.57	4700	266	0.051	0.00082	7.78E-03	2.24%	1.74E-04	0.1510	43.70	1.44
	1238.52	1440	76	0.016	0.00045	7.53E-04	2.34%	1.76E-05	0.5791	36.19	1.78
C	609.28	31000	1810	0.338	0.00210	1.03E-02	1.59%	1.64E-04	0.4611	71.12	1.47
	768.38	2830	117	0.031	0.00063	9.47E-03	1.83%	1.73E-04	0.0494	67.07	3.31
	934.16	1210	50	0.013	0.00041	8.75E-03	1.99%	1.74E-04	0.0303	50.61	3.41
	1120.57	4720	266	0.052	0.00082	7.78E-03	2.24%	1.74E-04	0.1510	43.90	1.45
	1238.5	1620	76	0.018	0.00048	7.53E-04	2.34%	1.76E-05	0.5791	40.97	2.11
D	609.27	27900	1810	0.302	0.00199	1.03E-02	1.59%	1.64E-04	0.4611	63.57	1.20
	768.35	2230	117	0.024	0.00056	9.47E-03	1.83%	1.73E-04	0.0494	52.24	2.35
	934.13	1010	50	0.011	0.00038	8.75E-03	1.99%	1.74E-04	0.0303	41.89	2.71
	1120.52	4220	266	0.046	0.00078	7.78E-03	2.24%	1.74E-04	0.1510	38.97	1.20
	1238.47	1400	76	0.015	0.00044	7.53E-04	2.34%	1.76E-05	0.5791	35.13	1.71

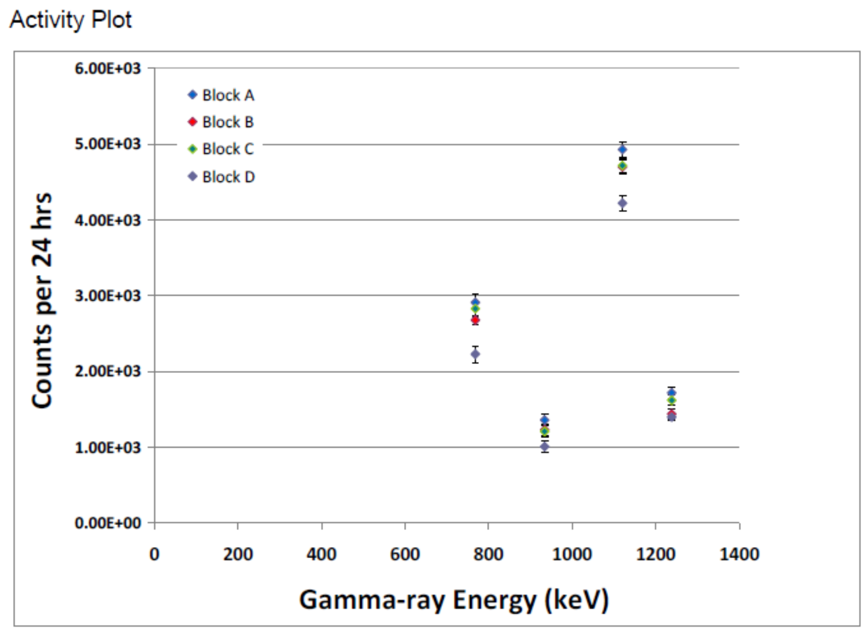

Figure 18. Graph of Gamma-Ray Peaks.

ECONOMIC ANALYSIS

This analysis utilizes the documented output of a commercially available automated block press as the basis for a conceptual economic analysis of the CEB that could be produced using waste clay. An adobe block machine from Powell and Sons, the PDA-600-12DP, can produce 600 blocks an hour.

600 blocks/hr. × 8 hr. /day = 4800 blocks/day

FUEL COST

The machine runs on diesel fuel, gasoline or electric power. For the purposes of this estimate we will assume liquid fuel at $3.00/gallon. A conservative estimate has the machine using 16 gallons of fuel/day, which yields the following fuel cost per block.

16 gallons of fuel/day × $3/gallon= $48.00/day
$48.00/4800= $.01/block

MATERIAL COST

The adobe machine requires 8 cubic yards of material per hour to produce 600 blocks. The material is a combination of sand, waste clay, Portland cement and fly ash, as described above. Based on the percentages of each material (by volume) used in the test mixtures and the current market price of each material, the following material costs can be estimated:

Portland Cement Cost

Seven percent Portland cement (PC) is added to the earth as a stabilizer in test mixtures #12 and #15.

- 8 yds.^{3}/hr. × 6% = .5 yds.^{3} of Portland cement/hr.
- .5 yds.^{3}/hr. × 8 hrs./day = 4 yds.^{3} of Portland cement/day
- One (1) 94 lb. bag of Portland cement = 1 cu. ft.
- 27 cu. ft./yd.^{3}
- 27 bags of cement/yd.^{3}
- 4 yds.^{3} × 27 bags/yd.^{3} = 108 bags of Portland cement
- 27 bags × $8.37/bag = $904
- $904/4,800 blocks = $.20/block

Sand Cost

In text mixture #15, 63% sand was used.

- 8 yds.^{3}/ hr. × 63% = 5 yds.^{3} of sand/hr.
- 5 yds.^{3}/ hr. × 8 hrs. = 40 yds.^{3} of sand/day
- Sand = 2,700 lbs./yd.^{3} × 40 yds.^{3}/day = 108,000 lbs./day
- 108,000 lbs./2,000 lbs./ton = 54 tons of sand/day
- 54 tons × $25/ton = $1,350/day
- $1,350/4,800 blocks = $.28/block

Fly Ash Cost

In test mixtures #12 and #15, 10% Class F fly ash (FA) was used.

- 8 yds.^{3} × 10% = .8 yds. of fly ash/hr.
- .8 yds.^{3}/hr. × 8 hrs./day = 6.4 yds.^{3} of fly ash/day
- 6.4 yds.^{3} × 2713 lbs./yd.^{3} = 17,361 lbs./day
- 17,361 lbs. × $.04/lb. = $694/day
- $694/4,800 blocks = $.14/block

Crushed Concrete Cost

In text mixture #12, 63% crushed concrete (CC) was used.

- 8 yds.^{3}/ hr. × 63% = 5 yds.^{3} of CC/hr.
- 5 yds.^{3} /hr. × 8 hrs. = 40 yds.^{3} of CC/day
- CC = 2,700 lbs./yd^3 × 40 yds.^{3}/day = 108,000 lbs./day
- 108,000 lbs./2,000 lbs./ton = 54 tons of CC/day
- 54 tons × $20/ton = $1,080/day
- $1,080/4,800 blocks = $.23/block

TOTAL MATERIAL AND FUEL COST

Test Block # 12:

- .23 (CC) + .14 (FA) + .20 (PC) + .01 (fuel) = $.58/block

Test Block #15:

- .28 (sand) + .14 (FA) + .20 (PC) + .01 (fuel) = $.63/block

The initial investment to begin producing blocks would include a small warehouse and machinery to dewater the clay, mix the soil, and compress the bricks.

Warehouse property -	$300,000
PEB-8a earth blender (Powell and Sons) -	$47,000
PDA-600-12DP pressed earth block machine-	$57,895
Shipping for both machines-	$6,000
Total initial cost:	$411,195

According to Advanced Earthen Construction Technologies, a producer of CEB machines, the current retail price in the U.S. of CEB without a stabilizer added is over $1.10 per unit. The cost of a hollow core concrete block is about $2.00 per unit. For a conservative estimate, we will assume a cost of $.60 to produce the CEB and a sales price of $1.10 for a $.50 profit per block.

To offset the initial costs of $411,195 with a profit of $.50 per block would require the production and sale of 822,390 blocks. With a production rate of 4800 blocks per day, it would take 171 days to produce 822,390 blocks.

822,390 blocks/4,800 = 171 days

To construct a one-story, 2000 square foot house from these blocks would require approximately 4320 blocks. The blocks produced in 95 days would be enough to build the following number of houses:

822,390/4,320 per house = 190 (2000 sq. ft. houses)

From this conceptual analysis, it seems entirely possible that a small business based on the production of blocks could be profitable in a relatively short amount of time. These findings are supported by Advanced Earthen Construction Technologies (AECT), who claim that the typical return on investment for their machinery is from 90-180 days (AECT 2010). The AECT estimate is based solely on the cost of machinery, while this analysis includes the cost of a warehouse and shipping, so it is thought to be a conservative estimate.

CONCLUSIONS

Testing performed with blocks made of waste clay from the phosphate industry and other recycled content revealed many promising aspects as well as several challenges to their adoption as a commercial product. Blocks were produced through a process of compaction, rather than firing, so the embodied energy and cost of production are both lower than with standard bricks. The test blocks contained only 7% Portland cement by volume, whereas concrete blocks are typically 16-17% by volume. The reduction in Portland cement results in a lower embodied energy and smaller carbon footprint. The performance of the compressed blocks was improved or stayed the same with the substitution of recycled materials as fine aggregate. Filtered, recycled concrete was used as a substitute for sand in Mixture #12 without significantly reducing the compressive strength. Given the same amount of clay and PC, the substitution of 10% fly ash for fine sand added to the workability of the mix, resulted in more uniform-looking bricks and significantly improved the compressive strength. Aside from the 7% Portland cement used as a stabilizer, Mixture #12 was entirely composed of recycled materials, making this mixture particularly attractive from an environmental perspective. This research utilized Class F fly ash because it was available locally. Additional research should be done using Class C fly ash to determine how its pozzolanic properties would affect the strength of the bricks.

According to the Florida Building Code, adobe blocks with a compressive strength of at least 300 psi can be used to make single- or two-story structures if designed by a professional engineer. Ten of the 16 test mixtures had a compressive strength above 300 psi and therefore would be suitable for use in building construction.

Absorption tests revealed that the block samples absorbed an average of 18.8% by weight and did not meet the FBC criteria of 2.5% moisture absorption by weight. More research and testing is necessary to determine how admixtures or sealers applied to the surfaces of the blocks could be used to reduce the amount of absorption. Tests performed on crushed samples showed a slightly elevated concentration of cadmium and a potentially high concentration of copper. The testing method exposed a maximum surface area and represents the high end of leached metals.

Gamma-ray measurements revealed that the sample blocks emit radon, as evidenced by the presence of Bi-214. The rate of radon emission in a hypothetical 27 m^3 volume with block walls was calculated to be substantially higher than EPA recommended levels. The high radon emission rates are thought to be partially due to the method of grinding the blocks into a powder form for testing purposes. More testing and research is necessary to determine the radon emission rate for blocks in their solid form and how the rate of radon emission could be reduced to acceptable levels through the use of ventilation, sealers, and additional materials and components attached to the block walls.

This project investigated the potential for using byproducts of the phosphate mining process and other recycled materials to make CEB. Because the blocks failed to meet some of the criteria established by the FBC and EPA, more testing is necessary to determine how these performance problems could be overcome. Once blocks are made that meet all of the necessary criteria, they could be commercialized through sister industries to the phosphate industry devoted to the production of CEB, providing an environmentally sound alternative to the waste clay retention ponds and an economic stimulus to the region.

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APPENDIX

EXCERPTS FROM 2007 FLORIDA BUILDING CODE

FBC 2109.8.1.1 Compressive strength- Adobe units shall have an average compressive strength of 300 psi (2068 kPa) when tested in accordance with ASTM C 67. Five samples shall be tested and no individual unit is permitted to have a compressive strength of less than 250 psi (1724 kPa).
FBC 2109.8.1.2 Modulus of rupture- Adobe units shall have an average modulus of rupture of 50 psi (345 kPa) when tested in accordance with the following procedure. Five samples shall be tested and no individual unit shall have a modulus of rupture of less than 35 psi (241 kPa).

FBC 2109.8.1.2.3 Testing procedure-.A vertical load shall be applied to the cylinder at the rate of 500 pounds per minute (37 N/s) until failure occurs.
FBC 2109.8.1.2.4 Modulus of rupture determination-The modulus of rupture shall be determined by the equation: fr=3WLs /2bt2 (Equation 21-4) where, for the purposes of this section only: b = Width of the test specimen measured parallel to the loading cylinder, inches (mm). fr = Modulus of rupture, psi (MPa). Ls = Distance between supports, inches (mm). t = Thickness of the test specimen measured parallel to the direction of load, inches (mm). W = The applied load at failure, pounds (N).

FBC 2109.8.2.1.2 Absorption tests- will be conducted after 28 days. A 4-inch (102 mm) cube, cut from a stabilized adobe unit dried to a constant weight in a ventilated oven at 212°F to 239°F (100°C to 115°C), shall not absorb more than 21/2 percent moisture by weight when placed upon a constantly water-saturated, porous surface for seven days. A minimum of five specimens shall be tested
and each specimen shall be cut from a separate unit.
FBC 2109.8.1.4 Shrinkage cracks- Adobe units shall not contain more than three shrinkage cracks and any single shrinkage crack shall not exceed 3 inches (76 mm) in length or 1/8 inch (3.2 mm) in width.