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List of Abbreviations

ASTM	American Society of Testing and Materials
Al_2O_3	Alumina
BGA	Biomass gasification ash
CaO	Calcium oxide (lime)
EIU	Eastern Illinois University
LOI	Loss on ignition
SEM	Scanning Electron Microscope

Abstract

Renewable energy offers a way to sustain the development of a society in harmony with nature and available resources (Das, 2007). As a renewable energy technology, biomass gasification has received revived attention recently. Nevertheless, responsible disposal or utilization of ash generated from biomass gasification process remains a technical challenge that needs to be resolved, in order for this technology to be a truly sustainable system (Fernandez-Pereira et al., 2011).

The overall objective of this study was to develop a unique, environmentally friendly technology to make value-added building materials from gasification solid waste, thereby managing solid waste efficiently and avoiding landfills, saving natural resources, and reducing greenhouse gas emissions. It is hoped that this investigation could benefit solid waste, gasification, and concrete/clay products industries, and could help protect the environment and communities. This project was also intended to explore the feasibility of using biomass gasification ash (BGA; a combination of fly ash and bottom ash) as an admixture in concrete materials. Cement production consumes a significant amount of energy. Biomass ash can be used to replace some portion of required cement in concrete mix as a sustainable construction practice, which can result in a significant energy savings to society. Through our lab-scale brick study, we determined that BGA can be used to replace clay and shale as raw materials in brick making. The replacement percentage level can be up to 10% by mass and 18% by volume. A concrete mix using 10% or 20% biomass gasification ash to replace cement was shown to have satisfactory compressive strength for field applications, typical of 3,000 psi grade concrete.

Executive Summary

The main goal of this project was to develop a unique, environmentally friendly technology to manufacture clay brick and concrete from biomass gasification solid waste, thereby managing gasification solid waste efficiently, saving natural resources, and reducing greenhouse gas emissions. The chemical composition of biomass gasification ash (BGA) depends on the feedstock used for biomass gasification, including wood chips, energy crops, agricultural residues, and other organic wastes (Fernandez-Pereira et al., 2011). Therefore, before optimizing formulations for concrete and clay products, we first characterized the raw materials to determine various mix proportions.

The study proceeded as follows:

1. Samples of BGA were obtained from the Eastern Illinois University biomass gasification facility. The raw materials of conventional masonry units such as cement, aggregates, clay, and shale were collected from industrial companies for characterization and comparison.
2. Representative samples of BGA prepared in the lab were characterized for chemical and mineralogical composition, including trace metals, metal oxides, lime (CaO), and loss on ignition (LOI) analysis. Based on the chemical and mineralogical composition, a number of formulations were worked out by selecting various mix proportions of these solid wastes on a weight percent basis. Furthermore, the most appropriate end-product (i.e., concrete or fired clay products) was determined based on the metal oxides and LOI content.
3. Masonry units (clay) and concrete cylindrical samples were prepared as per standard procedures in the lab. The samples of each formulation were tested according to the American Society of Testing and Materials (ASTM) standard for compressive strength and water absorption. All the results were analyzed and compared with the appropriate national standards for masonry units.
4. Data on costs of competing raw materials and finished products, including the environmental and disposal costs from production and use of these materials, were collected. The information obtained was used to conduct a preliminary techno-economic evaluation.

More than 45 bricks were produced by a bench-scale mold press method. These bricks were produced with formulations containing various amounts of biomass gasification ash, shale, and clay mixtures for evaluation. Firing was conducted using a bench-scale kiln. Through the lab scale brick study, we determined that BGA can be used to replace clay and shale as the raw materials in brick making. The replacement percentage level can be up to 10% by mass and 18% by volume. The concrete mix using 10% or 20% biomass gasification ash to replace cement was shown to have satisfactory compressive strength for field applications, typical of 3,000 psi grade concrete. Results of this investigation could lead to scaled-up production, demonstration, and possible commercialization of the process.

Chapter 1: Introduction

Renewable energy offers a way to sustain the development of a society in harmony with nature and available resources. As a renewable energy technology, biomass gasification has received revived attention recently (Das, 2007). Nevertheless, responsible disposal or utilization of ash generated from biomass gasification process remains a technical challenge that needs to be resolved, in order for this technology to be a truly sustainable system. In general, ash generated from the biomass gasification process has different characteristics than fly ash from direct combustion (Madlool et al., 2011). Compared to conventional combustion coal ashes, biomass gasification ash (BGA) generally has higher residual unreacted carbon, higher calcium oxide (CaO) content, more alkali (e.g., sodium [Na] and potassium [K]), higher specific surface area, less alumina (Al_2O_3) and silica (SiO_2), lower specific gravity, and lower soluble compounds (Das, 2007; Fernandez-Pereira et al., 2011). Additionally, the quality of BGA varies more than direct combustion ash depending on the composition and inorganic material in various feed-stocks used for gasification, such as wood chips, switch-grass, etc. (Leiva et al., 2007). Therefore, utilization of BGA is difficult unless pre-treated to eliminate unwanted chemical compounds, and commonly used methods for utilization of combustion fly ash in civil engineering materials cannot be directly applied to BGA. Variation in composition of BGA makes it a difficult waste material for utilization.

However, utilization of BGA in civil engineering materials or as blend component in the production of building products, such as fired clay bricks and concrete blocks, offers an attractive option to develop a sustainable form of utilization. It also has a relatively lower environmental impact. Earlier studies have shown successful use of coal combustion ash in the manufacture of concrete blocks and fired clay bricks (Chou et al., 2003). Coal combustion fly ash and BGA have some similar characteristics. Like coal combustion ashes, BGA also has self-cementing properties due to very high lime (CaO) content, potentially making it suitable to replace cement for making concrete masonry units (Chou et al., 2003). High amounts of unburned carbon (measured by LOI) is preferable for making fired clay and shale bricks, adding to the firing energy in the kiln when the bricks are fired (Chou et al., 2003). Therefore, this study aims to evaluate the feasibility of sustainable and economical utilization of biomass gasification byproducts such as fly ash and bottom ash for making concrete masonry blocks and fired clay bricks, while simultaneously replacing profligate greenhouse gas emitters (e.g., cement) and increasingly expensive clay and shale. The choice of final product, either concrete blocks or fired clay bricks, was made based on the characteristics of the BGA.

The overall objective of this study was to develop a unique, environmentally friendly technology to make value-added building materials from gasification solid waste, thereby managing solid waste efficiently, which in turn avoids landfills, saves natural resources, and reduces greenhouse gas emissions. We hope that this investigation could benefit solid waste, gasification, and concrete/clay products industries and also help protect the environment and communities.

Chapter 2: Experimental Study

2.1 Materials

The raw materials of conventional clay and shale bricks were collected from Glen Gery Brick in Marseilles, Illinois. Two types of samples with different proportions of clay/shale mixtures were collected; one sample had a mix of 84% shale and 16% clay, and another sample had a mix of 30% shale and 70% clay. Another sample of clay and shale was collected from the Colonial Brick Corporation in Cayuga, Indiana. Colonial Brick mines its clay and shale from a pit located on the plant property. The pure burning clay and shale were separately collected. It should be noted that all surface clay and shale mixtures were ground and screened at the respective plant and were ready to be used for forming bricks. All samples were collected in five gallon buckets and labeled. The fineness of clay and shale from Glen Gery Brick is greater than Colonial Brick Corporation. The fine and coarse aggregates for concrete samples were collected from Charleston Farrier Ready Mix. The origin of all concrete aggregates was Charleston Stone Company, which extracted the materials from the east side of Charleston, Illinois. The coarse aggregates were crushed limestone in three different sizes that later were sieved in the laboratory into particular physical mesh sizes to maintain the uniformity of the concrete mix. The biomass gasification ash samples (Figure 1) were collected in five gallon plastic buckets at a gasification facility at Eastern Illinois University (EIU). The feedstock for those biomass gasification ash was wood chips. The Renewable Energy Center at Eastern Illinois University consumes 30,000 tons of biomass annually, producing approximately 1,500 tons of ash as a byproduct. The cement and aggregate samples for the project were acquired from local commercial sources.

Figure 1: Biomass gasification ash.

2.2 Characterization of the Raw Materials

Chemical Characterization

The biomass ash samples, as well as the acquired clay, shale, clay/shale mix, cement (Portland cement type I), and aggregate raw materials, were analyzed by ALS Geochemistry Laboratory (Reno, NV) for chemical characterization. The chemical composition of the raw materials (biomass ash, clay, shale, clay/shale mix, cement, and aggregate) was determined and presented as metal oxide composition; the amount of unburned carbon was measured as the loss on ignition (LOI) value as shown in Table 1.

Table 1: Metal oxide compositions (wt. %) in fly ash, shale and clay samples.

Sample Description	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**Na_2O**	**K_2O**	**MnO**	**P_2O_5**	**C**	**LOI**
Biomass Ash from EIU	6.25	1.2	0.61	68.5	4.07	0.1	2.42	0.44	2.82	1.42	13.05
Biomass Ash (0-0.07366 mm)	3.86	0.55	0.49	70.3	4.53	0.03	2.62	0.45	2.5	2.46	13.5
Biomass Ash (0.07366-0.14986 mm)	6.4	0.92	0.59	71.1	4.39	0.04	2.48	0.41	3.13	1.76	9.87
Biomass Ash (0.14986-0.24892 mm)	8.07	0.98	0.71	74	3.84	0.03	2	0.36	3.25	1.19	7.23
Biomass Ash (0.24892-0.84074 mm)	9.45	1.28	0.73	71.7	3.68	0.04	1.84	0.38	3.04	0.99	5.92
Biomass Ash (> 0.84074 mm)	8.29	10.55	1.3	58.4	8.4	0.04	2.38	1.38	3.31	0.78	4.4
Fired Shale (100%)	57.7	17.65	8.09	0.59	1.99	0.85	3.23	0.08	0.16	0.66	6.63
Fired Clay (100%)	62.9	22.7	1.07	0.38	0.45	0.09	1.1	<0.01	0.05	0.33	9.72
Mixed Clay/Shale (16%/84%)	58.2	18.85	7.49	0.63	1.82	0.69	3.05	0.08	0.17	0.65	7.32
Mixed Clay/Shale (70%/30%)	61.2	21.3	4.07	0.54	1.06	0.35	2.07	0.03	0.11	0.43	8.74
Portland cement from EIU	18.95	4.44	3.19	61.9	2.43	0.15	0.56	0.08	0.06	0.65	3.45
Aggregate from EIU	1.93	0.4	0.68	53.1	0.47	0.03	0.06	0.16	0.05	11.95	42.4

A chemical characterization of various particle size fractions of the biomass ash sample was performed and summarized in Table 1. It can be seen that the biomass ash samples contained major oxides such as SiO_2, Al_2O_3, MgO, and the calcium oxide and LOI contents were relatively high, around 70% and 13%, respectively. According to the literature on fly ash bricks, the CaO content provides a guideline for selecting samples to avoid salt scum deposition on the surface of the bricks after firing. In general, CaO values of up to 6% are manageable in brick making to avoid scum deposition. As indicated in Table 1, the CaO values for the shale, clay and shale/clay mix samples (less than 1%) are much lower than those of the biomass ash samples (around 70%). The higher values for the CaO content and low values for SiO_2, Al_2O_3, and Fe_2O_3 in BGA samples are not beneficial for clay fire bricks but may be appropriate for concrete blocks. The CaO content of biomass ash is comparable with that of the Portland cement sample (around 62%). These ash samples may be used for bricks at a low proportion, beyond which the brick may show efflorescence. The LOI value indicates the amount of volatile matter that would be released during the firing process. The LOI values for the BGA samples were higher (up to 13.5%) than that for the clay and shale samples (9.72% and 6.63% by wt., respectively) used by the brick manufacturer.

Coarse aggregates used in the concrete cylinders were sieved to divide them into four categories, (1/4 inch, 3/8 inch, 1/2 inch and 3/4 inch) as shown in Figure 2. Aggregates larger than 3/4 inch in size were removed from the mix to avoid segregation. Figure 2 also shows the coarse aggregates after sieving.

Figure 2: Coarse aggregates after sieving.

Scanning Electron Microscope (SEM)

A scanning electron microscope (SEM) was used to study the microstructure and morphology of brick raw materials. SEM images were taken using a JEOL JSM-6060LV low vacuum scanning electron microscope (Frederick Seitz Materials Research Laboratory Central Facilities, University of Illinois). The voltage used was 20 kV, and the working distance was 10 cm.

Unit Weight

The unit weight of brick raw materials was measured according to ASTM C311. The ash used for unit weight measurement was pulverized ash (passing U.S. No. 200 sieve).

Particle Size Distribution

The particle size distribution of raw materials used for making both bricks and concrete has a great influence on the properties of green and fired bricks, particularly on absorption and strength. After grinding the ash to pass U.S. Sieve No. 200 (opening 0.075 mm), the particle size analysis was also performed for biomass ash to verify the effectiveness of grinding. Therefore, the particle size analyses were performed for all the raw materials: clay and shale mixture and biomass gasification ash (BGA).

2.3 Preparation of Brick Samples

For the brick application, the clay/shale mix and biomass ash were pre-mixed in a Doyon planetary mixer before adding water. Water was then added slowly and intermittently to achieve a homogeneous dough-like mixture. This dough-like mix of clay/shale and ash was placed in a metal mold under pressures of 500 to 1500 psi (3.4 to 10.3 MPa) applied by a hydraulic pressing machine. Various weight percentages of pulverized BGA ranging from 5% to 20% were evaluated as a replacement of clay and shale. The fresh brick samples were dried in a controlled temperature (25°C) and humidity (30-45%) environment in the laboratory to avoid rapid drying. The brick units were prepared as per the procedure previous used in the lab (Chou et al., 2003). Figure 3 shows some photos of fresh bricks after they were removed from the mold. Physical properties such as weight and dimensions were measured immediately after brick was made.

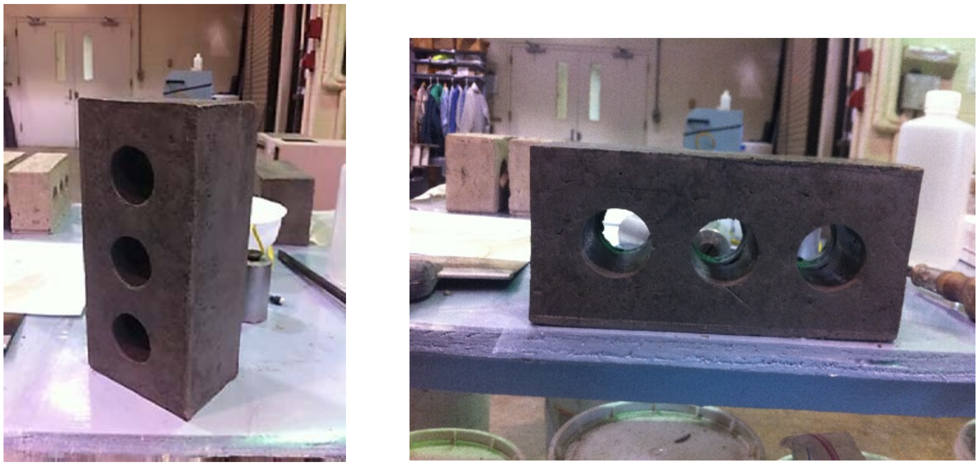


Figure 3: Brick unit after being removed from the mold.

2.4 Brick Firing

The kiln used for firing bricks is a bench furnace, L&L Special Furnace, Model GS 1714, which completes a firing cycle in approximately 40 hours. The kiln operation is controlled by a computer program. A typical firing cycle can be programmed to increase or hold temperatures for specific time intervals. The program shuts the kiln off once the firing cycle has been completed as programmed. Firing may be divided into five general stages: (1) final drying (evaporating free water); (2) dehydration; (3) oxidation; (4) vitrification; and (5) flashing or reduction firing. Although the actual temperatures will differ with clay or shale, final drying takes place at temperatures up to 300°F (149°C); dehydration from about 300°F to 1800°F (149°C to 982°C); oxidation from 1000°F to 1800°F (538°C to 982°C); and vitrification from 1600°F to 1931°F (871°C to 1055°C). After the temperature has peaked and is maintained for a prescribed time, the cooling process begins. Cooling is an important stage in brick manufacturing because the rate of cooling has a direct effect on the final product. A brick in the kiln after the firing cycle is shown in Figure 4.

2.5 Concrete Mixing

For the concrete application, the ratio of water, cement, fine aggregate, and coarse aggregate used for this study was: 0.6:1:2:4, respectively. Table 2 illustrates the proportions of ingredients used to make concrete mix.

Figure 4: Fired brick unit in kiln.

Table 2: Proportion of ingredients in concrete mix.

Ingredient	Amount
Water	12.15 lb
Cement	20.25 lb (maximum)
Ash	0, 10, 20% relative to total amount of cement. For example of 10% ash addition, 2.025 lb of ash, and 18.225 lb of cement were added into the concrete mix.
Fine Aggregate	40.50 lb
Coarse Aggregate	81.00 LB (48.5 lb of Retained on ½ inch, 19.5 lb of Retained on 3/8 inch, 13.0 lb of Retained on ¼ inch)

The biomass concrete mixing procedures were followed per the ASTM C192 method, using the drum mixer shown in Figure 5. The following procedure was used to load and mix the concrete batch:

1) Loaded half the volume of coarse aggregate to the mixer;
2) Added the prescribed amount of sand (i.e., fine aggregate);
3) Placed the water into the mixer;
4) Added the remainder of the aggregates (coarse aggregate);
5) Mixed the mixture (without cement and ash) for two minutes;
6) Added the required amount of cement;
7) Mixed the mixture (without ash) for two minutes;
8) Added ash of the required amount (10 or 20% relative to the total cement to be added);
9) Mixed the mixture for two minutes;
10) Performed a slump test using the procedure given below.

Figure 5: Drum mixer used for biomass concrete.

Forming and Hydrating Concrete Samples

To form and test cylindrical samples at different curing times by hydration, we used the following protocol:

1) For all concrete samples with each ash percentage, we prepared concrete quantities as indicated in Table 2; this was poured into 24 cylinder forms sized 3 in. (diameter) × 6 in. (height);
2) Concrete samples were released from forms after 24 hours +/- 2.0 hours;
3) Concrete samples were immersed in clear tap-water in a hydration tub until the compression test dates;
4) Compression strength tests were scheduled and performed at 7, 14, 28, and 60 days;
5) Freezing/defrosting strength tests were performed at 60 days and with only one 24-hour cycle of freezing and 24 hours of defrosting prior to the tests;
6) Four cylinders for each compression test were cured at 7, 14, and 28 days; three of four were tested for compression strength analysis, and one was kept uncrushed for comparison in the laboratory;
7) Eight cylinders for 60-day testing were prepared, three of which were tested as a control sample without freezing and defrosting, three were tested for freezing and defrosting as described on item number 5 above, and two samples were kept uncrushed for comparison in the laboratory;
8) All concrete cylinders were numbered sequentially and data including date, type of concrete, etc. were recorded on a log sheet.

Testing Cylinders Preparation and Forming Procedures:

For making and curing concrete test specimens, ASTM C192/C192M-14 Standards were followed, as summarized below:

1) Marked all cylinders with required information as described in item 7 above (in Forming and Hydrating Concrete Samples procedure);
2) Applied a generous amount of form release inside each cylinder;
3) Taped the bottom hole of the form from outside of the mold to avoid concrete outflow;
4) Filled approximately 1/3 of the cylinders with mixed concrete;
5) The concrete was compacted by the rod and tap method: a 3/8 inch round-ended rod and the rubber mallet were used as described in rodding/tapping section;
6) Filled another 1/3 of mixed concrete into the cylinders, and repeated rodding and tapping procedures;
7) Filled the rest of the cylinders to the rim with the concrete mixture, then followed the rodding/tapping procedures;
8) If required, the top empty part of the cylinders were filled to the rim with concrete mix;
9) Topped off to the rim any excess concrete mix with a flat metal trowel. Used gentle motions to avoid causing segregation of materials;
10) Avoided rodding and/or tapping after step 8;
11) Cleaned the rim and exterior sides of the cylinders with clean rag or paper towels;
12) Covered the lid and placed cylinders inside the hydration tub in an upright position.

Rodding and Tapping Procedures:

1) Placed required amount of concrete into the mold for the first layer (1/3 of the mold, about 2 inch);
2) Rodded the first layer 25 times to the entire depth (2 inch) of the mold and concrete, distribute the strokes evenly over the mold;
3) Placed the second layer of the concrete inside the mold;
4) Rodded for 25 times the second layer to the entire depth and additional 1.0 inch into the first layer, (3 inch deep rodding);
5) Placed the third and final layer of concrete inside the mold;
6) Rodded 25 times to the depth of the third layer with additional depth of 1.0 inch into the second layer;
7) After adding each layer and prior to adding another, tapped the outside of the mold 10 times with rubber mallet;
8) To complete the molding process, followed Testing Cylinders Preparation and Forming Procedures outlined above.

2.6 Concrete Compressive Strength Test

Compression tests (ASTM C39) determine the compressive strength of concrete (or its ability to resist a crushing force). In this test, a standard test load is applied parallel to the longitudinal axis of a pre-molded and properly cured concrete cylinder of a standard size (4 in × 8 in). When the test is properly conducted, a maximum load is obtained at the point at which the cylinder ruptures. With this maximum load, the compressive strength, measured in pounds per square inch (psi), can be easily calculated. Compressive strength of cylindrical concrete samples made with BGA was tested using a SATEC/Instron universal testing machine (shown in Figure 6).

Figure 6: Typical sample loading in a universal testing machine.

The following parameters were used for the compressive strength testing per ASTM C39 standards:

- Sample supports: A cylindrical sample was supported with two steel sleeves on both ends. The steel sleeves provided good contact with the stationary and moving plates on the universal testing machine.
- Loading rate: After the play was eliminated between the sample and plates, a loading rate of 2000 psi/min was maintained.
- Fracture mode: Continual observation or monitoring was conducted during the entire compression test. Fracture mode was observed for each sample under compressive stress until after the breakage.
- Premature failure: If any of the sample ends was crushed prematurely, a note was made and the atypical data was eliminated. This type of premature collapse is typically also evidenced by a dip on the load-time curve.

Chapter 3: Results and Discussion

3.1 Particle Size Distribution and Unit Weight of Biomass Ash

The particle size distribution of raw materials used for making bricks has a great influence on properties of green and fired bricks, particularly on absorption and strength. The particle size of biomass ash was reduced (passing U.S. Sieve No. 200, opening 0.075mm) to improve the homogeneity of the raw materials throughout the mixture. After grinding, a particle size analysis was performed on the biomass ash to verify the effectiveness of grinding. The particle size distribution curves of raw biomass ash, pulverized biomass ash passing No.200, and shale/clay mixture are shown in Figure 7.

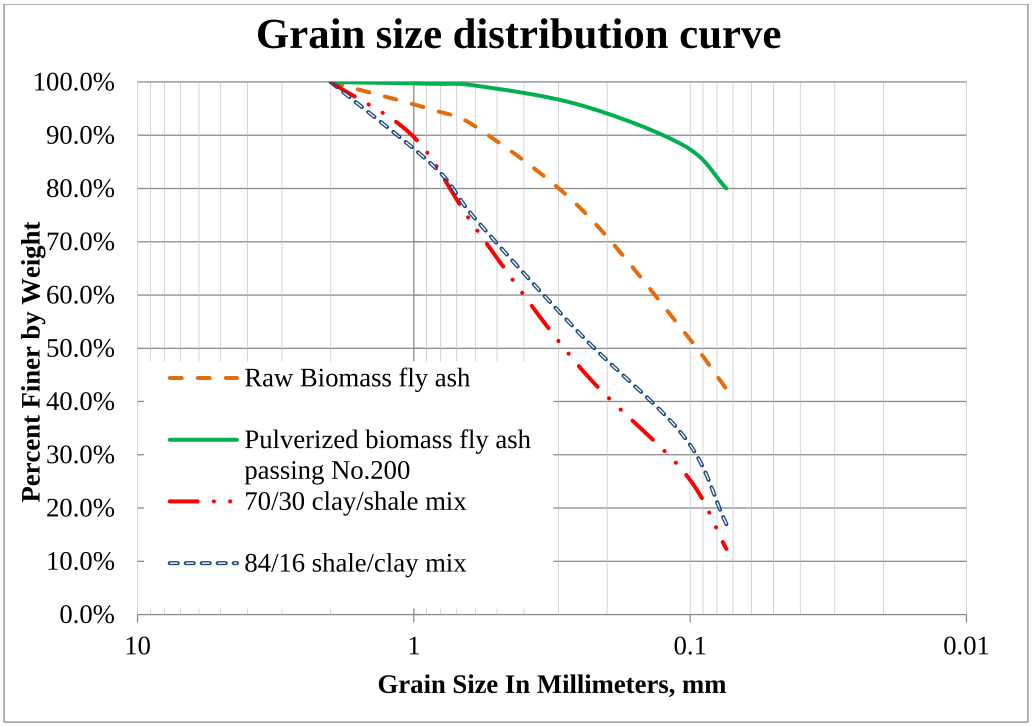


Figure 7: Particle size distribution curve.

The biomass ash sample shows particle sizes ranging from 0.1 to 2 mm, with the majority smaller than 0.2 mm (Figure 7); thus, biomass ash particle size was significantly decreased after grinding. The grinding effectiveness of biomass ash was very good, with 80% of biomass ash particles reduced to 0.070 mm.

The unit weight of biomass ash was measured for the ash passing No. 200 sieve. Table 3 summarizes the average unit weight of biomass ash and clay/shale mixture. It can be seen that the unit weight of biomass ash is much less than the conventional Class C fly ash. Without close compaction, the unit weight of biomass ash is only 34-54 lb/ft^3. Table 4 shows the biomass ash replacement percentage in volume fraction in the bricks. Since the unit weight of biomass ash is very low, the 10% replacement by mass converts to 18% volume in one brick.

Table 3: Unit Weight of Raw Materials.

	Clay/shale	**Biomass ash**	**Class C fly ash**
Unit weight:	125 lb/ft^3	55-65 lb/ft^3	75-95 lb/ft^3
		without close compaction	
		34-54 lb/ft^3	

Table 4: Biomass ash replacement percentage by volume.

Replacement percent (by mass)	5%		10%		15%	
	by mass	by volume	by mass	by volume	by mass	by volume
clay/shale	95%	91%	90%	83%	85%	76%
biomass ash	5%	9%	10%	18%	15%	24%
water	varies by ash %	varies by ash %	varies by ash %	varies by ash %	varies by ash %	varies by ash %

3.2 Scanning Electron Microscope (SEM) Analysis

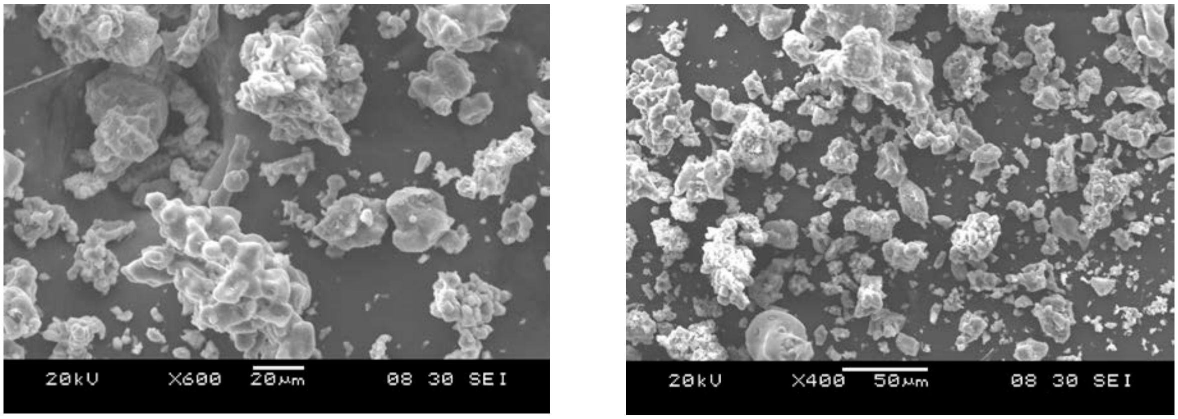
The typical scanning electron microscope (SEM) images for the samples of BGA and clay/shale mix used for bricks are shown in Figure 8 and Figure 9, respectively. The SEM analysis indicated that the biomass ash sample was characterized by a significant amount of non-spherical and porous particles, whereas the clay/shale mix was characterized by flat stacked particles. Non-spherical particles make biomass ash consume more water when mixed with clay/shale because non-spherical particles have irregular shapes which cannot easily fit into the gaps between particles of shale and clay. Porous morphology makes BGA absorb more water than Class C spherical fly ash (shown in Figure 10).

3.3 Water Requirement of Mixtures for Plasticity

Figure 11 illustrates water needs (average of two batches) for homogeneous mix dough with various BGA replacement percentages. It can be seen that all the batches have higher water needs than pure clay/shale mix without BGA ash.

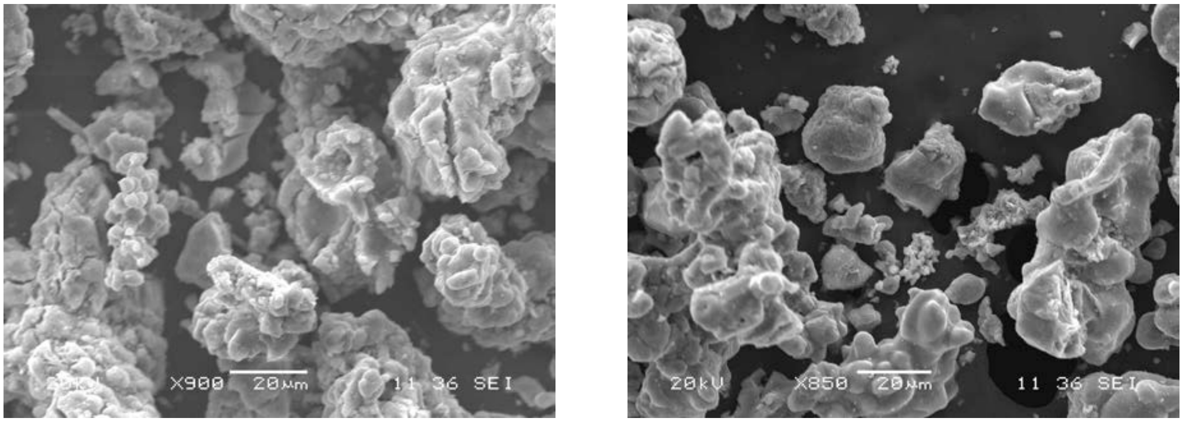
The higher water demand of BGA mixtures could arise from the irregular particle shape, highly porous and non-spherical morphology (shown in SEM images in Figure 8), and the higher CaO content (shown in Table 1, composition of BGA).

High water demand is not beneficial for clay bricks. After capillary water is lost, individual molecules undergo size reduction, resulting in irreversible shrinkage. Most of the cracking in these bricks occurs due to shrinkage at the time of initial drying. In general, the greater the quantity of water used in the mix, the greater the shrinkage. This is visible in Figure 12, illustrating that 20% ash replacement had severe expansion and cracks after firing, while 10% ash replacement had a fewer cracks. The 10% ash replacement showed only surface cracking and had no severe expansion after firing. Therefore, the goal is to reduce the water needs to reach the same plasticity of the mixture.



a) Pulverized ash b) Pulverized ash

Figure 8: Scanning electron microscope (SEM) images of BGA.



a) 70%/30% clay/shale mix b) 16%/84% clay/shale mix

Figure 9: Scanning electron microscope (SEM) images of clay and shale mix.

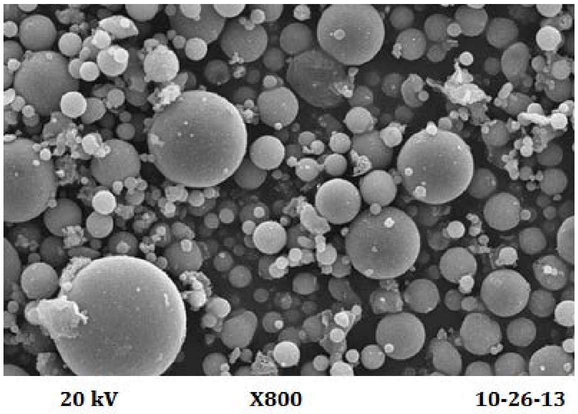


Figure 10: Scanning electron microscope (SEM) image of Class C fly ash.

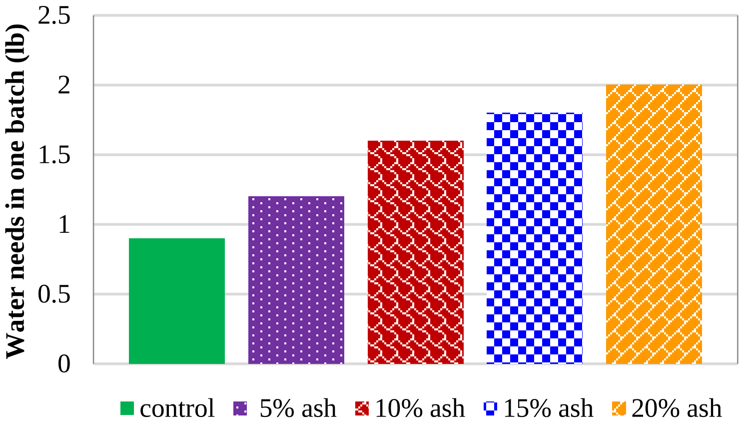


Figure 11: Water needs as BGA replacement percentage.

Figure 12: Surface cracking and expansion in bricks after firing (10%, 15%, and 20% ash from left to right).

3.4 Brick Making and Firing

Figure 13 shows the fired bricks with different ash replacement percentages. The color of bricks lightened as biomass ash replacement increased. The weight of bricks also decreased as the biomass ash replacement increased. Ash replacement from 5-10% by mass remained in great condition during drying and firing, but beyond 10% ash replacement by mass, the bricks exhibited problems during drying and final firing stages, such as shrinkage, surface cracks during drying, and expansion during firing. Some bricks with 15% ash replacement didn't show surface cracking during normal drying but showed expansion cracking during final firing (middle brick in Figure 12).

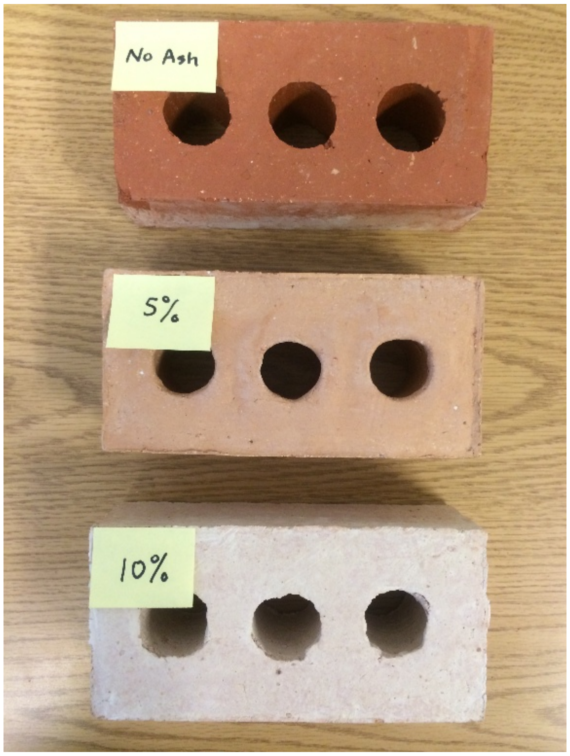


Figure 13: Fired bricks with different ash replacement percentages.

The main reason for the surface cracking and expansion in high replacement percentage (15%-20%) bricks is probably due to the high CaO content in biomass ash. The high CaO content, combined with low values for SiO_2, Al_2O_3, and Fe_2O_3 in biomass ash samples, is not beneficial for bricks because the hydration of lime after brick formation causes a reduction in the volume of the system of silica - lime - water. This reduction causes surface cracks as the clay body shrinks to varying degrees during the drying process. Stresses build up within the brick, influenced by the properties of the clay and its degree of plasticity. Therefore, differential drying can cause shrinkage, and lumps of drier material will shrink differently than the rest of the brick. In order to solve this problem, the following approaches can be used: reducing the particle size of raw materials; achieving a homogeneous mix by allowing sufficient mixing time for the dry ingredients before adding water; and increasing the mixing time after adding water but before molding. In addition, high compaction pressure produces less shrinkage through the monitoring of the brick dimensions in the normal drying stage. Based on our lab measurements, brick dimensions are more stable when using high compaction pressure. Moreover, the content of ligno-sulfonate can be increased, allowing less water to be used, making clay and shale mixtures more plastic, and increasing the adhesion of the clay plates. Through these remedial actions, the cracking in bricks showed moderate improvements.

3.5 Brick Compressive Strength and Absorption

Building Bricks

ASTM C62 (Table 5) specifies that building bricks must have a minimum compressive strength of 2,500 psi for Grade SW (severe weathering) for an individual brick, or 3,000 psi for an average of five bricks measured. If the cold water absorption is less than 8%, then the boiling water absorption test and saturation coefficient specifications are waived. Otherwise, the maximum boiling water absorption allowed is 20% for an individual brick or 17% for an average of five bricks. The water absorption is a major factor for the durability of bricks; high absorption of water would contribute to a rapid deterioration of this type of material.

The building brick samples prepared in this study were tested for compressive strength and water absorption. As shown in Table 6, all bricks with 2.5%, 5%, and 10% BGA met the building brick ASTM specifications for the negligible weathering grade (Grade NW). Five percent BGA bricks met Grade MW (moderate weathering) and 2.5% BGA bricks met Grade SW specifications.

Table 5: ASTM C62 - Standard specifications for building brick.

ASTM C62 Grade Designation	Minimum Compressive Strength gross area, psi (MPa)		Maximum 24-hrs Cold Water Adsorption, 8%*			
			Maximum Water Absorption by 5-hrs Boiling, %		Maximum Saturation Coefficient**	
	Average of 5 Bricks	Individual Brick	Average of 5 Bricks	Individual Brick	Average of 5 Bricks	Individual Brick
Grade SW	3,000 (20.7)	2,500 (17.2)	17.0	20.0	0.78	0.80
Grade MW	2,500 (17.2)	2,200 (15.2)	22.0	25.0	0.88	0.90
Grade NW	1,500 (10.3)	1,250 (8.6)	No limit	No limit	No limit	No limit

**Absorption Alternate* – The saturation coefficient requirement does not apply, provided that the 24-h cold water absorption of each of the five units tested does not exceed 8.0 %.

**The saturation coefficient is the ratio of absorption by 24-h submersion in cold water to that after 5-h submersion in boiling water.

Grade SW (Severe Weathering) –Brick intended for use where high and uniform resistance to damage caused by cyclic freezing is desired and where the brick may be frozen when saturated with water.

Grade MW (Moderate Weathering) – Brick intended for use where moderate resistance to cyclic freezing damage is permissible or where the brick may be damp but not saturated with water when freezing occurs.

Grade NW (Negligible Weathering) – Brick with little resistance to cyclic freezing damage but which are acceptable for applications protected from water absorption and freezing.

Paving Bricks

ASTM C902 (Table 7) specifies that paving bricks must have a minimum compressive strength of 7,000 psi for Class SX (severe weathering) for an individual brick, or 8,000 psi for an average of five bricks measured. If the cold water absorption is less than 6%, then the boiling water absorption test and saturation coefficient specifications are waived. Otherwise, the maximum cold water absorption allowed is 11% for an individual brick or 8% for an average of five bricks. The water absorption and abrasion resistance (Table 8) are major factors for the durability of bricks; high absorption of water and abrasion would contribute to a rapid deterioration of this type of material.

The paving brick samples prepared in this study were tested for compressive strength and water absorption. As shown in Table 9, all the bricks with 2.5%, 5%, and 10% BGA met the paving brick ASTM specifications for the Class MX – brick intended for exterior use where resistance to freezing is not a factor.

Table 6: Compressive strength and water absorption of BGA building bricks.

	BGA replacement percentage	**Control (0%)**	**2.50%**	**5%**	**10%**	**15%**
Mechanical property	Compressive strength, psi	4634	3938	2630	1782	1450
Physical property: Max. water absorption	Cold water 24 hr, %	3.70%	4.20%	6.77%	7.50%	15%
	Boiling water 5 hr, %	5.25%	6.70%	11.52%	18%	23%

Table 7: ASTM C902 - Standard specification for pedestrian and light traffic paving brick.

ASTM C902 Class Designation	Minimum Compressive Strength gross area, psi (MPa)		Maximum 24-hrs Cold Water Adsorption, 6%*			
			Maximum Cold Water Absorption, %		Maximum Saturation Coefficient**	
	Average of 5 Bricks	Individual Brick	Average of 5 Bricks	Individual Brick	Average of 5 Bricks	Individual Brick
Class SX	8,000 (55.2)	7,000 (48.3)	8.0	11.0	0.78	0.80
Class MX	3,000 (20.7)	2,500 (17.2)	14.0	17.0	No limit	No limit
Class NX	3,000 (20.7)	2,500 (17.2)	No limit	No limit	No limit	No limit

* *Absorption Alternative* – If the average water absorption is less than 6.0 % after 24-h submersion in room temperature water, the requirement for saturation coefficient shall be waived.

**The saturation coefficient is the ratio of absorption by 24-h submersion in cold water to that after 5-h submersion in boiling water.

Class SX – Brick intended for use where the brick may be frozen while saturated with water.

Class MX – rick intended for exterior use where resistance to freezing is not a factor.

Class NX – Brick not intended for exterior use but which may be acceptable for interior use where protected from freezing when wet.

Table 8: ASTM C902 - Standard Specification for Pedestrian and Light Traffic Paving Brick.

ASTM C902 Type	Abrasion Index*, Max.	Volume Abrasion Loss**, Max. cm$^{3/}$cm^{2}
Type I	0.11	1.7
Type II	0.25	2.7
Type III	0.50	4.0

*The abrasion index is calculated from the cold absorption in percent and the compressive strength in pounds per square inch as follows: Abrasion Index = (100 * absorption)/compressive strength

**The abrasion resistance should be determined according to Column 2 in those cases where the procedural requirements for compressive strength cannot be met.

Type I – Brick subjected to extensive abrasion. Type I pavers would be used in such places as sidewalks and driveways in publicly occupied spaces.

Type II – Brick subjected to intermediate abrasion. Type II pavers would be used in such places as heavily traveled residential walkways and residential driveways.

Type III – Brick subjected to low abrasion. Type III pavers would be used in such places as floors or patios in single-family homes.

Table 9: Compressive strength and water absorption of BGA paving bricks.

	BGA replacement percentage	**Control (0%)**	**2.50%**	**5%**	**10%**	**15%**
Mechanical property	Compressive strength, psi	6,724	5,997	4,637	3,019	2,526
Physical property: **Max. water absorption**	Cold water 24 hr, %	3.20%	7.39%	9.17%	11.52%	15.69%
	Boiling water 5 hr, %	8.37%	10.91%	15.98%	18.71%	22.99%

3.6 Freeze-Thaw Test for Bricks

According to ASTM C67 – Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile, the Freezing and Thawing test for bricks involves soaking brick units in water at 75 ± 10°F (24 ± 5.5°C) for four hours and freezing them at 16°F (-9°C) for 20 hours. After each fifth cycle the brick units are air dried for 40 hours at room temperature. The weight loss must be less than 3% and no visible cracks should be found. Due to limited availability of freeze-thaw instruments, only 30 cycles were performed for the bricks. The maximum weight loss was 2.2% for the building bricks containing 15% BGA.

3.7 Concrete Compressive Strength

According to American Society of Testing and Materials (ASTM) standard C55 (Table 10) for concrete building bricks, the required compressive strength is 2,500 psi (average of 3 units) and 2,000 psi (individual unit). As per ASTM standard C90 (Table 11) for load bearing concrete masonry units, the required compressive strength is 2,000 psi (average of 3 units) and 1,800 psi (individual unit). As per ASTM standard C1634 (Table 12) for concrete facing brick, the requirement is 3,500 psi for an average of 3 units and 3,000 psi for an individual unit.

The samples prepared for this exploratory research were tested for compressive strength, and the data indicated that even with up to 20% biomass ash, the concrete material can still perform satisfactorily for the above mentioned applications. Figure 14 and Table 13 illustrate the compressive strength of concrete mix as a function of curing time (days) for concrete samples of various compositions. It is noted that the compressive strength increased with curing time for all samples.

Table 10: ASTM C55 – 11- Standard specification for concrete building brick.

Classification	Average of 3 units	Individual Units
Light Weight	2,500 (17.2)	2,000 (13.8)
Medium Weight	2,500 (17.2)	2,000 (13.8)
Normal Weight	2,500 (17.2)	2,000 (13.8)

Minimum Net Area Compressive Strength, lb/in^2 (MPa)

Table 11: ASTM C90 – 14 - Standard specification for loadbearing concrete masonry units.

Classification	Average of 3 units	Individual Units
Light Weight	2,000 (13.8)	1,800 (12.4)
Medium Weight	2,000 (13.8)	1,800 (12.4)
Normal Weight	2,000 (13.8)	1,800 (12.4)

Minimum Net Area Compressive Strength, lb/in^2 (MPa)

Table 12: ASTM C1634 – 11 - Standard specification for concrete facing brick.

Classification	Average of 3 units	Individual Units
Light Weight	3,500 (24.1)	3,000 (20.7)
Medium Weight	3,500 (24.1)	3,000 (20.7)
Normal Weight	3,500 (24.1)	3,000 (20.7)

Minimum Net Area Compressive Strength, lb/in^2 (MPa)

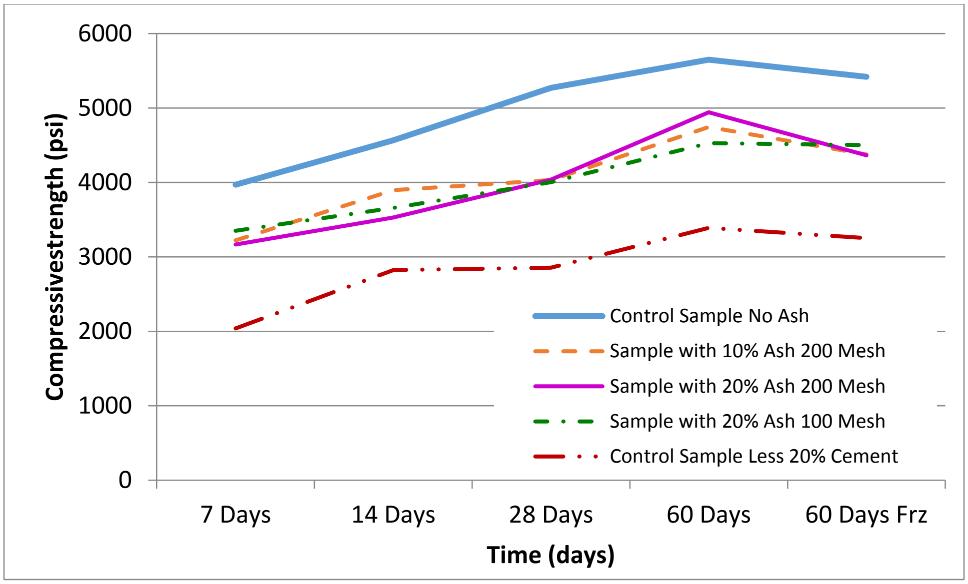


Figure 14: Effect of biomass ash and curing time on compressive strength on concrete.

Table 13: Compressive strength in psi as a function of curing (hydration) time for samples prepared for this study.

	7 Days	**14 Days**	**28 Days**	**60 Days**	**60 Days Frozen**
Control Sample No Ash	3,969	4,567	5,270	5,650	5,420
Sample with 10% Ash 200 Mesh	3,222	3,897	4,032	4,745	4,376
Sample with 20% Ash 200 Mesh	3,166	3,530	4,039	4,943	4,364
Sample with 20% Ash 100 Mesh	3,352	3,659	4,003	4,528	4,502
Control Sample Less 20% Cement	2,039	2,822	2,855	3,390	3,252

As a result of one cycle of deep freeze and thaw, all concrete samples exhibited a general decline in compressive strength. This pattern of property change with curing time is typical for all normal concrete materials. In other words, adding up to 20% of biomass gasification ash did not alter the basic behavior of concrete materials.

The compressive strengths of concrete samples with the addition of 10% or 20% biomass gasification ash of 0.150 mm or 0.075 mm were comparable to each other. They were all lower than the compressive strength of control samples, which contained the full amount of cement and no BGA.

It is noted from Figure 15 that the concrete sample with 20% less Portland cement showed the lowest strength. Its compressive strength did not pass the 3,000 psi mark after 28 days of curing. For practical purposes, this type of concrete mix will not be accepted for field applications.

As biomass gasification ash was added to the concrete mix (10% or 20% of cement weight), the compressive strengths showed a significant increase compared with control samples with 20% less cement. For example, after 28 days, the concrete mix with 10% or 20% ash showed a compressive strength of 4,000 psi. This fact indicates a beneficial effect of using biomass gasification ash in concrete materials.

3.8 Techno-Economic Analysis

To find potential applications for the biomass gasification ash, we have identified four potential sites or companies near the Renewable Energy Center at Eastern Illinois University. Table 14 lists the relevant data for the four companies, including cost of cement and transportation costs of biomass gasification ash from the Renewable Energy Center at Eastern Illinois University.

Table 14: Cost of cement and transportation cost of biomass gasification ash to nearby plants.

	Charleston Ferrier Ready Mix	Coles County Concrete	Mattoon Ready Mix	Illinois Brick
Location (City)	Charleston	Charleston	Mattoon	Champaign
Distance from Renewable Energy Center of EIU (mile)	1	5	10	50
Cost of Cement from Suppliers ($ per ton)	$110 (St. Louis)	$110 (St. Louis)	$110 (St. Louis)	$110 (Chicago)
Cement Transportation Cost ($ per ton)	$5.9	$5.9	$5.9	$5.9
Subtotal of cement cost, as delivered to the concrete plants ($ per ton)	$115.90	$115.90	$115.90	$115.90
Transportation cost of biomass gasification ash from EIU to destination	$3	$3	$3	$4

Currently, the biomass gasification ash from EIU's Renewable Energy Center is disposed in a landfill in Effingham County, approximately 35 miles away. The total disposal cost of the ash is approximately $80 per ton.

Preliminary data from this project has shown a beneficial effect of biomass gasification ash when added to the concrete mix. For example, at 28 days, the compressive strength of concrete with the full amount of cement was around 5,270 psi, while the compressive strength of concrete mix with 20% less cement was reduced to 2,855 psi. Upon the addition of 20% biomass gasification ash (i.e., replacing 20% cement with biomass ash), the concrete mix reached a compressive strength of approximately 4,000 psi.

The preliminary data indicated that biomass gasification ash can be used to replace cement in concrete material, which can still perform satisfactorily for the above mentioned applications. An analysis was conducted on the cost savings and the environmental impact of using biomass gasification ash in concrete materials. Due to the proprietary nature, the company name will be omitted in this case study (Table 15).

Table 15: A case study on the cost saving.

Total Amount of Cement Used by the Company Per Year (ton)	6,675	
Assumed Percentage of Cement to be Replaced by Biomass Gasification Ash	10%	20%
Total Amount of Cement to be Replaced by Biomass Gasification Ash (ton)	668	1,336
Cost Savings from Replaced Cement ($)	$77,421	$154,842
Cost Savings for Ash Disposal by EIU	$53,440	$106,880
Ash Transportation Cost from EIU to Cement Plant	($2,004)	($4,008)
Total Cost Savings per Year (Cement Plant and EIU)	$128,857	$257,714
Energy Savings from Replaced Cement (1.427 MBTU per ton) Per Year	953 MMBTU	1,906 MMBTU
Expected Reduction in CO_2 Emission from Cement Production (ton of CO_2)	668 tons of CO_2	1,336 tons of CO_2

In the US, one ton of cement production consumes about 141 kWh of electrical energy and 4.6 GJ of thermal energy (Madlool et al, 2011). That is, the total energy consumption of cement production is 1.427 MMBTU (0.481 MMBTU + 0.948 MMBTU).

In summary, the resulted energy savings would amount to 953 MMBTU if 10% of cement is replaced by biomass gasification ash, 1,906 MMBTU if 20% of cement replaced. The total reduction in CO_2 emission will be 668 tons per year if 10% of cement is replaced, and 1,336 tons if 20% of cement is replaced. The total cost savings to the community (both the cement plant and the Renewable Energy Center at EIU) will be $128,857 per year if biomass gasification ash is used to replace 10% of cement, or $257,714 per year if 20% cement is replaced.

For the brick application, the economic feasibility of producing fired bricks with BGA is an important factor to consider in the commercialization. The major factors to be considered in an economic assessment are the cost of obtaining biomass gasification ash and the cost of brick production with conventional materials. The disposal cost of BGA is $80 per ton. The total mining and grinding costs for conventional raw materials such as clay and shale is around $5.10 per ton, which will be saved by using the readily available BGA. The transportation cost of BGA is around $5.90 per ton. Considering utilization of 1,500 tons of BGA generated at the EIU facility for making fired clay bricks:

- The savings in disposal fees will be $120,000
- The transportation cost of the BGA to the brick plant will be $8,850
- The mining and grinding cost saving of 1,500 tons of clay and shale will be $7,650
- The total cost saving will be $118,800 by substituting 1,500 tons of BGA for clay and shale

This case study of one leading U.S. brick manufacturer, equipped with a fully-computerized, state-of-the-art operation system, having capacity to manufacture 120 million bricks per year shows significant savings. Considering 10% (by wt.) substitution of BGA for clay and shale, it would be 0.5 pounds BGA for each brick; therefore, the manufacture of 120 million bricks per year could consume 30,000 tons of BGA per year. For the transportation cost, a trucking company quoted a rate of $5.90/ton for shipping BGA 150 miles from EIU plant to a brick manufacturer. The annual cost for transporting 30,000 tons of BGA would be $177,000. Mining & grinding costs for clay and shale material for 120 million bricks per year is estimated at $1,531,000. Substituting 10% (by wt.) with BGA could reduce production cost by $153,100 per year. BGA disposal cost is $80/ton, and the cost for 30,000 tons BGA costs $2,400,000 per year. Overall, the estimated annual cost saving could be nearly $2,400,000.

Chapter 4: Conclusions and Recommendations

Through the lab scale brick study, we have shown that BGA can be used to replace clay and shale as the raw materials in brick making. Through the particle size reduction of BGA, high content of admixture (ligno-sulfonate) usage to increase plasticity and reduce cracking, and increased compaction pressure during brick production, the replacement percentage level can be up to 10% by mass and 18% by volume. Future work could explore the benefit of the high CaO content (cementitious materials potential) in biomass ash and improve the ash replacement level in brick. Experimental data on compressive strength showed a beneficial effect of adding biomass ash to concrete mixtures. The concrete mix using 10% or 20% biomass gasification ash to replace cement was shown to have satisfactory compressive strength for field applications, typical of 3,000 psi grade concrete. The above promising effects were found with fine particles of ash. For example, experimental data showed biomass ash of both 0.150 mm and 0.075 mm had comparable positive effects on concrete strength (around 4500-4900 psi, up to 20% ash). More systematic study of the effect of ash particle size and various ash treatments is needed in order to produce consistent results for sustainable field applications. Due to the particle size distribution of the biomass gasification ash, this study only demonstrated a beneficial effect of fine particle ash. The fine powder of ash (0.150 mm and 0.075 mm) only represents a fraction of the total ash generated from the gasification process. Thus, more study will be needed to understand the effect of ash particle sizes in order to fully utilize all ash. Large scale industrial applications require consistent materials to maintain high quality of materials and construction projects. To achieve a consistent ash supply, it is imperative that we explore ways to treat biomass gasification ash, including (but not limited to) ash size reduction, de-carbonization, and slurry processing. A long term durability study for the concrete mix is needed before further recommendations can be made for the wide adoption of biomass gasification ash as an effective admixture of sustainable construction materials.

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