# Evaluation of the Mixture Compositions of Fly Ash, Sludge and Binder to Produce LWA by the Pyro-process and Production of a Bulk Quantity of LWA for ASTM Specification Tests

**by**

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## EXECUTIVE SUMMARY

In August 2001, the LWA Consortium of North Carolina requested the NC State Minerals Research Laboratory (MRL) to evaluate the proper mixture composition for the production of synthetic lightweight aggregate (LWA) from coal combustion ash, and paper sludge. The objective was to determine the mixing combination of fly ash, waste sludge and binder to produce LWA pellets that will meet all the ASTM specifications for structural concrete application and to produce a bulk quantity of LWA for testing.

The procedure for producing the lightweight aggregate was based on the patented pyro-process designed and awarded to Svedala Industries in a 1995 US Patent No. 5,057,009 by Nechvatal et al. Thus, the described research program was non fundamental but applied. However, some aspects of the processes, especially mixing of the materials and manufacturing of the pellets by tumbling was unique. Also, the biomass used in combination with the coal ash was unique in composition since

the sludge was from non wood pulp, flax. The program included bench-scale tests that produced disc pellets using a hydraulic press, spherical pellets by tumbling in a rotating cylinder and extruded pellets using an extrusion machine. Finally, several batches of bulk green pellets (approximately 15.0 lb per batch) were produced to generate enough bulk LWA material for the ASTM testing. The goal was to produce about 200 pounds of coarse angular lightweight aggregates for ASTM C-331-00 specification testing.

The solid byproducts feed for making the synthetic lightweight aggregate included combustion coal ash (fly ash and bottom ash) from Progress Energy of Carolinas, non-wood paper (flax) sludge from RFS Ecusta, and wood pulp and paper sludge from Blue Ridge Paper Company. Mixture ratios of 80-87% coal ash and 5 -16% sludge were evaluated. The ash consisted of 90% by weight of Progress Energy's ash and 10% Ecusta's coal ash. In some of the tests, fine perlite from Miller Perlite Company, Morganton, NC was used as a substitute for binder and sludge at the weight ratio of 2.5 - 10.0%. Carboxymethylcellulose (CMC-T) and bentonite were used as binders at the weight addition of zero to 7.3%. Dried pellets from the bench scale tests were fired in a laboratory muffle furnace. The procedure for producing bulk quantities of pellets consisted of mixing the component byproduct materials in the large Muller Mill and producing pseudo-spherical pellets by tumbling the mixture in a rotating steel cylinder (an 8" x 8" laboratory rod mill without the rods). Mixture ratios of 85 - 89% ash and 11-15% sludge were used, and the ash consisted of 90% by weight of Progress Energy's ash and 10% Ecusta's ash.

The standard procedure for firing was to preheat the furnace to the firing temperature before placing the dry pellets contained in a fireclay dish. Firing temperatures ranged from 1800° F to 2200° F and the soaking time at the firing temperature was between 30 minutes and 2 hours. Bulk quantities of dry pellets were fired at the Brick Research Center at Clemson University using their Swindel-Dressler Periodic gas-fired furnace. The firing procedure consisted of placing the dry pellets in fused silica crucibles in the furnace and raising the temperature at about 20° F per minute until the firing temperature of 2200° F was attained.

In most cases, the pellets produced after firing small batches in the muffle furnace were bloated, vitrified, strong and lightweight. Varying size gradations of the fired pellets were produced with varying specific gravity and unit density (pounds per cubic feet) during the bench-scale tests. The moisture content of the green pellets was 33-44% without the addition of external liquid. Mixture composition at 36% moisture produced finer sized green pellets whereas same mixture composition with 44% moisture resulted in coarser sized green pellets by tumbling. Mixtures with higher than 44% moisture were too wet and resulted in few large balled pellets. Mixtures with lower than 36% moisture were too dry to ball and did not produce pellets.

Firing temperatures below 1800° F resulted in the production of unvitrified pellets with weaker strength. At firing temperatures between 2000 and 2200° F the pellets were vitrified with high strength. Since the pellets stayed in the fireclay dish without movement, they stuck to each other during the melting stage. The product after firing had to be crushed to separate individual pellets. This process of breaking the pellets resulted in weakening of the pellets because some of the break occurred through the pellets. Pellets that were not broken but maintained their shapes were stronger than those that were broken into several pieces.

The measured specific gravity of the fired pellets ranged from 0.9 to 1.80 with coarser pellets having lower specific gravity. The loose unit density for the fired pellets was in the range of 25 lb/cu ft to 55 lb/cu ft. Coarser pellets had unit density below 49 lb/cu ft whereas finer pellets had loose density greater than 50 lb/cu ft. The water of absorption was 11 to 28%

ASTM C-330-00 specification tests were performed by Froehling & Robertson, Inc. of Asheville using the standard 6-bag cement mix. The anticipated 28-day compressive strength of 5,000 to 6,000 psi was not achieved. The measured 28-day compressive strength was 3250 psi. The lower compressive strength was due to the weaker strength of the crushed pellets.

The bench-scale tests showed that pseudo spherical pellets could be made from the available stock of byproduct materials to generate dry pellets with reasonable strength for firing. The green pellets were fired to produce lightweight aggregates of the desired strength, desired lose unit density, desired specific gravity and desired size gradations. The major stumbling block in the investigation was the unavailability of a rotary kiln to fire bulk quantities of pellets to the desired vitrified form and strength. It has been established that movement of the pellets in a rotary kiln during firing is essential for better heat transfer and production of higher strength pellets without the need for subsequent crushing. Although, bench-scale tests were useful for evaluating the process parameters, it is important to have a rotary kiln to be able to perform the proper firing procedure. This is necessary to produce aggregates with the desired shape and strength.

## INTRODUCTION AND BACKGROUND

In October 2000, The North Carolina State Minerals Research Laboratory (MRL) a division of College of Engineering at NCSU initiated a program that brought industry, academia and state agencies together as a consortium to evaluate the production of lightweight aggregates (LWA) in Western North Carolina. The initial partners in the consortium included from industry: Progress Energy of Carolinas, Inc, Asheville, RFS Ecusta, Brevard, Blue Ridge Paper Product, Inc. Canton, General Shale Brick, Kingsport, TN, Appalachian Products, Inc., Johnson City, TN, and Metropolitan Sewerage District of Buncombe County, Asheville; from Academia: North Carolina State University Minerals Research Laboratory, Asheville; and from State Agencies: North Carolina State Department of Environmental and Natural Resources, Waste Reduction Partners/ Land-of-Sky Regional Council, and North Carolina Department of Transportation. Some of the industry partners have since left the Consortium whiles other industry partners have joined the consortium. The current industry partners of the Consortium are Progress Energy (formerly CP&L) of Asheville, RFS Ecusta of Brevard (went out of business in August 2002), Jackson Paper Manufacturing Company of Sylva, and ReUse Technology, Inc. of Woodstock, GA. These partners have a stake in waste reduction and management in North Carolina and are interested in the conversion of the high volume solid waste into a value added and a benign product. Each partner brings a unique perspective and knowledge about waste reduction and management in North Carolina.

Majority of solid wastes (on the basis of volume) generated by local industries in Western North Carolina are coal combustion by-products (CCB), municipal waste sludge and pulp and paper sludge. Progress Energy of the Carolinas, Inc. (formerly CP& L) of Asheville, RFS Ecusta, Brevard, Jackson Paper Manufacturing Company, Sylva, and Blue Ridge Paper Products, Inc. of Canton are the major generators of coal combustion by-products. RFS Ecusta, Blue Ridge Paper and Metropolitan Sewerage District of Buncombe County (MSD) are the producers of paper and pulp sludge and municipal waste sludge.

At the April 2001 meeting of the consortium, the Minerals Research Laboratory was asked to prepare a research plan for detail bench tests to evaluate the proper mix of components that will result in the production of LWA to meet the appropriate ASTM specifications. The procedure for producing the lightweight aggregates was based on the patented pyro-process designed and awarded to Svedala Industries in 1995. Thus, the described research program was non fundamental but applied. However, some aspects of the processes, especially mixing and manufacturing of the pellets by tumbling was unique. Also, the biomass used in combination with the coal ash was unique in composition since the sludge was from non-wood pulp, flax.

These tests were to vary the composition of fly ash, sludge, and binder in a mixture, and to determine the unit weight of the synthetic LWA after firing. In addition, a single batch test was performed to prepare 3/8" angular LWA by extrusion method using the services of J.C. Steele & Sons, Inc. in Statesville, North Carolina. Other variables investigated included firing temperature, firing sequence and firing time. After determining the optimum conditions (fly ash, biomass and binder mixture, firing sequence, temperature and time), approximately 30 pounds of LWA were produced using the optimum mixture compositions.

The program included bench-scale tests to produce disc pellets using a hydraulic press, spherical pellets by tumbling in a rotating cylinder and extruded pellets using extrusion machine all from the byproduct materials provided by the industry partners. Initially mixing of the raw byproduct materials was done with a spatula in a stainless steel pan. Finally, a laboratory Muller Mill was used for mixing and the spherical pellets were made by tumbling the mixed components in a laboratory rod mill without the rods. The green pellets were dried in a laboratory oven to remove moisture and also to increase the strength of the pellets. The dry pellets were heated to the firing temperature in a bench top muffle furnace. Approximately thirty batch tests were performed to produce small amounts (about 1.0 lb at a time) of fired pellets in a laboratory muffle furnace. Majority of these tests (about twenty-five) used Progress Energy's fly ash and Ecusta's sludge whereas the other tests used Blue Ridge Paper's ash and sludge. These tests used varying mixture compositions and firing conditions to produce the lightweight pellets.

In most cases, the pellets produced after firing small batches in the muffle furnace were bloated, vitrified, strong and lightweight. Varying size gradations of the fired pellets were produced with varying specific gravities and unit weights (pounds per cubic feet).

Finally, several batches of bulk green pellets (approximately 15.0 lb per batch) were produced to generate enough bulk material to produce LWA for the ASTM testing. A total of 200 lb of dry pellets was produced during the period of the program. It was anticipated that the rotary kiln at MRL would be used to fire these bulk pellets after drying but the kiln did not become operational during the period of the program. Therefore, the bulk dry pellets were taken to the Brick and Tile Research Center at Clemson University for firing in their Swindel-Dressler Periodic gas fired furnace. The firing procedure at the Brick Research Center was not effective, and only 25% of the dry pellets were converted to bloated vitrified pellets acceptable as lightweight aggregates. In essence 75% of the manufactured dry pellets were wasted and could not be converted into LWA. Although, the converted fired pellets were bloated, vitrified and lightweight (desired unit weight) yet they lacked the desired strength. Consequently, the ASTM specification tests C-331-00 performed with the aggregates did not produce the expected compressive strength.

In order to achieve the desired strength and unit density, the fired pellets should vitrify, bloat and not be broken. Broken vitrified pellets had the desired unit weight but they lacked the strength and also tended to absorb excessive water.

## STATEMENT OF THE PROBLEM

In August 2001, the LWA Consortium of North Carolina requested the NC State Minerals Research Laboratory (MRL) to evaluate the proper mixture composition for the production of synthetic lightweight aggregates (LWA) from coal combustion ash, and paper sludge. The objective was to determine the mixing combination of fly ash, waste sludge and binder to produce LWA that will meet all the ASTM specifications for structural concrete application and to produce a bulk quantity of LWA for testing and evaluation.

The procedure for producing the lightweight aggregates was based on the patented pyro-process designed and awarded to Svedala Industries in 1995 US Patent No. 5,057,009 by Nechvatal et al. The program included bench-scale tests that produced disc pellets using a hydraulic press, spherical pellets by tumbling in a rotating cylinder and extruded pellets using an extrusion machine. Finally, several batches of bulk green pellets (approximately 15.0 lb per batch) were produced to generate enough bulk material to produce LWA for the ASTM testing. The goal was to produce about 200 pounds of coarse angular lightweight aggregates for ASTM C-331-00 specification testing.

## METHODOLOGY

### I. Sample Description and Preparation:

The following streams of by-products were identified in the local region and were available for the synthetic lightweight aggregates' production:

A. Combustion Ash (Fly Ash and Bottom Ash)

(i) Progress Energy (CP&L): ponded combined fly ash and bottom ash in wet form at

70% solids (30% MOI). 300-450 tons/day dry basis of combined with 16 - 25% LOI

(ii) RFS Ecusta: fly ash in dry form at about 97% solids(3%MOI). 40 tons/day (dry basis) with 10-16% LOI. RFS Ecusta Company ceased operation in August 2002 but their ash is contained in a mono fill (landfill) at the site in Brevard.

(iii) Jackson Paper Manufacturing Company: wood ash in dry form at about 97% solids (3% MOI). 3-5 tons/day (dry basis)

(iv) Blue Ridge Paper Company: coal combustion fly ash in dry form at about 97% solids (3% MOI). About 156 tons/day (dry basis) with 23% LOI.

B. Sludge

(i) RFS Ecusta: paper flax sludge in wet form at 45% MOI (55% solids). 17.5 tons/day (dry basis). RFS Ecusta Company ceased operation in August 2002 but the landfill containing the sludge is available at the site. It has been estimated that up to 1.0 million tons of sludge were accumulated over the years in the landfill. All the previous tests used the waste sludge that came from the operation of the plant and not from the landfill.

(ii) MSD: municipal waste sludge in wet form at 45% MOI (55% solids). 5.2 tons/day (dry basis)

(iii) Blue Ridge Paper Company: pulp, paper and mill wastewater sludge at 45% MOI (55% solids). 122 tons/day (dry basis)

(iv) Hendersonville Water and Sewer: municipal waste sludge at 45% MOI (55% solids). 2.5 tons/day (dry basis)

C. Other Byproduct materials

(i) Miller Perlite: fine perlite powder in dry form at about 98% solids (2% MOI). 12.5 tons/month (dry basis)

(ii) Other Sludge Products: from various sources in the local region

The weight distributions of combustion ash from the industry partners are 90.1%, 9.0 % and 0.9% for Progress Energy, RFS Ecusta and Jackson Paper respectively. All the sludge for this project was supplied by RFS Ecusta. Since the combustion ash from Jackson Paper was not significant (only 0.9%), it was not used for the current project tests. The ash from Jackson Paper will be used in future tests for the production of the bulk samples for market evaluation. On the basis of the patented pyro-process, the mixture compositions were 35 - 99 % combustion ash and 1-65% sludge on dry weight basis. All the by-product materials were used as received without any prior preparation.

**II. Bench-scale Tests**

Bench-scale batch studies to determine proper mix of Progress Energy's ash with Ecusta's sludge were performed. Mixture ratios of 80-87% ash and 5 -16% sludge were evaluated. The ash consisted of 90% by weight of Progress Energy's ash and 10% Ecusta's ash. In some of the tests, fine perlite from Miller Perlite Company, Morganton, NC was used as a substitute for binder and sludge at the weight ratio of 2.5 - 10.0%. Carboxymethylcellulose (CMC-T) by Hercules, Inc. and bentonite were used as binders at the weight addition of 0-2.7%.

The procedure included tests that produced disc pellets using a hydraulic press, spherical pellets by tumbling in a rotating cylinder and extruded pellets using an extrusion machine. Initially mixing of the raw byproduct materials was done with a spatula in a stainless steel pan. Finally, a laboratory Muller Mill was used for mixing and the spherical pellets were made by tumbling the mixed components in a laboratory rod mill without the rods. The green pellets were dried in a laboratory oven to remove moisture and also to increase the strength of the pellets. The dry pellets were heated to the firing temperature in a bench top muffle furnace. Approximately thirty batch tests were performed to produce small amounts (about 1.0 lb at a time) of fired pellets in the laboratory muffle furnace.

**III. Production of Bulk Quantities of LWA**

Several batches of bulk green pellets (approximately 15.0 lb per batch) were produced to generate enough bulk LWA for ASTM specifications testing. The procedure consisted of mixing the component by-product materials in the large Muller Mill followed by tumbling the mixture in a rotating cylinder (an 8" x 8" laboratory rod mill without the rods) to produce pseudo-spherical pellets. Mixture ratios of 85 - 89% ash and 11-15% sludge were used, and the ash consisted of 90% by weight of Progress Energy's ash and 10% Ecusta's ash.

**IV. Firing of Dry Pellets to produce the Lightweight aggregates (LWA)**

Dry pellets from the bench scale tests were fired in a laboratory muffle furnace. The standard procedure for firing was to preheat the furnace to the firing temperature before adding the dry pellets that were contained in a fireclay dish. The firing temperature ranged from 1800° F to 2200° F and the soaking time was between 30 minutes and 2 hours.

Bulk amounts of dry pellets were fired at the Brick Research Center in Clemson University using their Swindel-Dressler Periodic gas-fired furnace. The firing process involved placing the dry pellets in fused silica crucibles in the furnace. The temperature was then raised at about 20° F per minute until the firing temperature of 2200° F was attained. The soaking time at the firing temperature was one and half to two hours.

**V. Size Gradation of the Fired Pellets**

Since the pellets stuck to each other during firing, it was necessary to break the pellets to separate the individual particles. The clumped fired pellets were crushed in the laboratory jaw crusher at the full open position of the discharge end. Particle size anslysis was performed on some of the fired pellets from the bench tests using the following sieves: 3/4", 3/8", 1/4", 4 US Mesh, 6 US Mesh, 8 US Mesh 18 US Mesh.

**VI. Quality Control**

Quality control for LWA production tests typically includes the following: (I) loss-on-ignition (LOI) for the raw byproduct materials (coal ash, sludge, perlite, or other biomass), (ii) specific gravity, (iii) bulk loose unit density in lb per cu ft, (iv) water absorption, (v) gradation of the pellets, (vi) compressive strength, (vii) abrasion tests for the fired pellets, (viii) TCLP Test for the fired pellets, (ix) mineral analysis and ultimate analysis of the raw byproduct materials , (x) ASTM Specification tests

Although, most of these quality control parameters could not be determined at our facilities here in Asheville yet a few of the product samples were subjected to specific gravity, water absorption, gradation and bulk lose density determinations. The results of these tests are tabulated in Tables included in this report. Also, approximately 30 pounds of bulk aggregates was produced and submitted for ASTM C-330 tests. The tests were performed by an outside licensed laboratory, Froehling & Robertson in Asheville.

## DISCUSSION OF RESULTS

### Bench-scale Tests

Table 1 shows the mixture compositions for preparing the green pellets. The moisture content of the green pellets ranged from 33 to 44% without the addition of external liquid. The particle size distribution of the dry pellets for Test 31, Test 32, and Test 33 are listed in Table 2. Mixture composition with lower moisture content produced finer sized green pellets whereas mixture composition with higher moisture content produced coarser sized green pellets. Mixtures with higher than 44% moisture were too wet and resulted in few large balled pellets. Mixtures with lower than 36% moisture were too dry to ball and did not produce pellets.

In most cases, the pellets produced after firing small batches in the muffle furnace were bloated, vitrified, strong and lightweight. The physical properties of the fired pellets (product aggregates) are shown in Table 3. Varying size gradations of the fired pellets were produced with varying specific gravity and unit density (pounds per cubic feet). The measured specific gravity of the fired pellets ranged from 0.9 to 1.80 with coarser pellets having lower specific gravity. The loose unit density for the fired pellets was in the range of 40 lb/cu ft to 55 lb/cu ft. Coarser pellets had unit density below 49 lb/cu ft whereas finer pellets had loose density greater than 50 lb/cu ft. The water of absorption was 11 to 28%

Firing temperatures below 1800° F resulted in the production of unvitrified pellets with weaker strength. At the firing temperatures between 2000 and 2200° F the pellets were vitrified with high strength. Since the pellets stayed in the fireclay dish without movement, they stuck to each other during the melting stage and the product had to be broken to separate individual pellets. Also some of the pellets stuck to the fireclay dish and had to be scraped from the dish. This process of breaking the pellets resulted in weakening of the pellets because some of the break occurred through the pellets. Fired pellets that were not broken but maintained their shapes were stronger than those that were broken into several pieces.

The procedure used to fire the bulk quantities of the dry pellets resulted in the vitrification of less than 25 wt- % of the dry pellets, 60 wt-% unfired low LOI fine ash and about 14 wt-% non bloated unvitrified pellets. The vitrified pellets stuck to each other in the crucible and they had to be crushed to break them apart. The crushing process resulted in the production of weak aggregates.

ASTM C-330 Specification Testing

ASTM C-330 specification tests were performed by Froehling & Robertson, Inc. of Asheville using the standard 6-bag cement mix. The anticipated 28-day compressive strength of 5,000 to 6,000 psi was not achieved. The measured 28-day compressive strength was 3250 psi. The lightweight aggregates produced by the procedures described above did not have the expected strength due to the process of firing and crushing of the fired aggregates. Firing in a rotary kiln will eliminate these problems and result in stronger aggregates that would probably meet the specified compressive strength.

## CONCLUSIONS

The bench-scale tests have shown that pseudo spherical pellets could be made from the available stock of byproduct materials to generate dry pellets with reasonable strength for firing. The green pellets could then be fired to produce lightweight aggregates of the desired strength, desired lose unit density, desired specific gravity and desired size gradations. The major stumbling block in the investigation was the unavailability of a rotary kiln to fire bulk quantities of pellets to the desired vitrified form and strength. It has been established that movement of the pellets in the kiln during firing is essential for better heat transfer and production of higher strength pellets without the need for subsequent crushing. Although, bench-scale tests were useful for evaluating the process parameters and to optimize the process, it is important to have a rotary kiln to be able to perform the proper firing procedure. This is necessary to produce aggregates with the desired shape and high strength.

## RECOMMENDATIONS FOR FUTURE WORK

It is apparent from the results of the work done so far that a rotary kiln is required to fire the pellets to produce individually vitrified, bloated and strong aggregates. The next phase of the research program cannot be effectively implemented without the availability of a rotary kiln for firing the pellets. Although, the laboratory muffle furnace could be used to fire small quantities of dry pellets and produce good lightweight aggregates, production of bulk quantities of LWA for evaluation and ASTM specification tests will not be feasible without a rotary kiln. Therefore, a rotary kiln capable of firing up to 200 lb per hour of pellets should be procured for the next phase of the research program. All the other equipments for preparing the green pellets are available at the MRL facility in Asheville.

In view of the uncertainty with RFS Ecusta's sludge, other sludge from the region should be identified and evaluated for their suitability for making lightweight aggregates. The sludge deposited in the landfill at Ecusta's property should also be evaluated.

A systematic bench-scale evaluation of proper mix of byproduct materials and process parameters to produce the desired LWA product should be pursued. Some of the variables to be investigated will include but not limited to the use of processed coal ash with lower LOI values, firing sequence, firing atmosphere in the kiln, soaking time, cooling conditions, and rate of heat transfer.

Preliminary market analysis should be conducted to identify the (a) competition, (b) current production levels by competitors, (c) cost of production, (d) current LWA demand in the local region, (e) current price of LWA ,(f) potential and target markets in the region including (i) structural concrete and masonry units, (ii) lightweight abrasive aggregates for asphalt pavements, (iii) sound absorption barriers, (iv) landscaping, soil conditioning and decorative ground cover, and (v) refractory concrete

Finally, bulk quantities (hundreds of pounds) of LWA should be produced for market evaluation and testing

**Table 1. Mixture Compositions and Test Conditions for Preparing Pellets**

| Test No | Weight Percent (%) Addition | | | | % MOI | Mixer/Releaser |
|---|---|---|---|---|---|---|
| | Ash | Sludge | Perlite | Binder[1] | | |
| 2 | 84.0 | 13.3 | 0.0 | 2.7 | 40.0 | Blend Tech |
| 3 | 86.6 | 10.8 | 0.0 | 2.6 | 38.5 | Blend Tech |
| 4 | 82.4 | 10.3 | 0.0 | 7.3 | 38.0 | Blend Tech |
| 5 | 86.1 | 10.1 | 7.3 | 2.4 | 36.7 | Blend Tech |
| 6 | 78.9 | 18.8 | 0.0 | 2.3 | 42.6 | Blend Tech |
| 7 | 87.9 | 9.5 | 0.0 | 2.6 | 36.7 | Blend Tech |
| 9 | 86.2 | 13.3 | 0 | 0.5 | 39.0 | Blend Tech |
| 10 | 84.4 | 13.1 | 0.0 | 2.5 | 39.1 | Blend Tech/Celite |
| 11 | 81.9 | 15.8 | 0.0 | 2.3 | 44.1 | Blend Tech |
| 12 | 83.4 | 16.1 | 0.0 | 0.5 | 44.7 | Blend Tech |
| 13 | 83.4 | 16.1 | 0.0 | 0.5 | 44.0 | Blend Tech/Celite |
| 14 | 83.8 | 16.2 | 0.0 | 0.0 | 44.6 | Blend Tech |
| 15 | 91.2 | 8.3 | 0.0 | 0.5 | 37.5 | Blend Tech |
| 16 | 88.1 | 11.4 | 0.0 | 0.5 | 41.0 | Blend Tech |
| 17 | 94.5 | 5.0 | 0.0 | 0.6 | 34.9 | Blend Tech |
| 18 | 83.0 | 7.2 | 9.4 | 0.5 | 35.4 | Blend Tech |
| 19 | 80.8 | 15.1 | 3.6 | 0.5 | 44.7 | Blend Tech |
| 20 | 98.7 | 9.8 | 0.0 | 0.5 | 39.3 | Blend Tech/Pine Oil |
| 21 | 81.4 | 9.6 | 8.8 | 0.4 | 39.2 | Blend Tech/Pine Oil |
| 22 | 94.8 | 5.2 | 0.0 | 0.0 | 30.6 | Scrubber/Celite |
| 23 | 85.7 | 11.4 | 2.8 | 0.0 | 38.0 | Scrubber/Celite |
| 24 | 86.7 | 10.3 | 3.0 | 0.0 | 40.2 | Scrubber/Celite |
| 25 | 86.7 | 10.3 | 3.0 | 0.0 | 40.2 | Scrubber/Celite |

| | | | | | | |
|---|---|---|---|---|---|---|
| 26 | 81.6 | 12.3 | 6.1 | 0.0 | 36.8 | Scrubber/Fly Ash |
| 27 | 83.0 | 14.4 | 2.6 | 0.0 | 35.5 | Scrubber |
| 28 | 76.2 | 10.1 | 8.6 | 2.6 | 34.1 | Extruder |
| 31 | 89.7 | 9.8 | 0.0 | 0.5 | 36.1 | Muller Mill |
| 32 | 84.8 | 14.6 | 0.0 | 0.5 | 40.0 | Muller Mill |
| 33 | 86.8 | 12.7 | 0.0 | 0.5 | 39.1 | Muller Mill |
| 34 | 80.2 | 13.1 | 8.5 | 0.0 | 36.8 | Muller Mill |
| 35 | 79.3 | 14.1 | 6.6 | 0.0 | 38.9 | Muller Mill |
| 36 | 86.5 | 13.1 | 0.0 | 0.4 | 39.5 | Muller Mill |
| 37 | 86.4 | 13.2 | 0.0 | 0.4 | 39.0 | Muller Mill |
| 38 - 50 | 86.3 | 13.2 | 0.0 | 0.4 | 36-40 | Muller Mill |

Notes:

All test used carboxy methyl cellulose except Test No. 4 that used bentonite clay
Ash composition was 90.0 wt-% Progress Energy and 10.0 wt-% Ecusta
Test No. 36 to 50 produced bulk quantities of pellets (15.0 lb per batch)

**Table 2. Particle Size Distribution of Dry Pellets as a Function of Moisture Content of Mixture**

| | Test No. 31 (36 % Moisture) | | | Test No. 32 (40% Moisture) | | | Test No. 33 (39% Moisture) | | |
|---|---|---|---|---|---|---|---|---|---|
| Mesh Size | Wt. g | Wt- % Retained | Cum % Retained | Wt. g | Wt-% Retained | Cum % Retained | Wt. g | Wt-% Retained | Cum % Retained |
| 3/8" | 34.7 | 14.3 | 14.3 | 42.0 | 18.7 | 18.7 | 40.8 | 17.9 | 17.9 |
| 1/4" | 72.2 | 29.8 | 44.1 | 79.5 | 35.5 | 54.2 | 72.9 | 32.0 | 49.9 |
| 4 | 75.0 | 30.9 | 75.0 | 52.0 | 23.2 | 77.4 | 63.0 | 27.7 | 77.6 |
| 6 | 50.3 | 20.8 | 95.8 | 39.1 | 17.4 | 94.8 | 36.5 | 16.0 | 93.6 |
| 8 | 6.3 | 2.6 | 98.4 | 8.8 | 3.9 | 98.7 | 4.6 | 1.9 | 95.7 |
| 18 | 0.5 | 0.2 | 98.6 | 0.4 | 0.2 | 98.9 | 0.5 | 0.2 | 95.9 |
| Pan | 3.5 | 1.4 | 100.0 | 2.4 | 1.1 | 100.0 | 9.4 | 4.1 | 100.0 |
| Total | 242.5 | 100.0 | | 224.2 | 100.0 | | 227.7 | 100.0 | |

**Table 3. Physical Properties of Fired Pellets (Lightweight Aggregates)**

| Test No | Ash/Sludge Ratio, % | Product Size | Specific Gravity | Loose Density lb/cu ft | % Water Absorption |
|---|---|---|---|---|---|
| 2 | 84.0/13.3 | + 3/8" | N/A | 27.6 | N/A |
| 3 | 86.6/10.8 | + 3/8" | N/A | 26.5 | N/A |
| 4 | 82.4/10.3 | + 3/8" | 1.07 | 25.5 | 20.5 |
| | | 3/8 " x 1/4" | 1.07 | 30.1 | 16.5 |
| | | 1/4" x 1/8" | N/A | 34.7 | N/A |
| | | - 1/8" | N/A | 52.4 | N/A |
| 5 | 86.1/10.1 | + 3/8" | 0.98 | 30.1 | 3.7 |
| | | 3/8" x 1/4" | 0.97 | 28.6 | 26.4 |
| 11 | 83.8/16.2 | + 3/8" | 1.16 | 30.3 | 24.0 |
| 12 | 83.4/16.1 | + 3/8" | 1.11 | 27.3 | 14.4 |
| | | 3/8" x 1/4" | 1.11 | 31.4 | 16.2 |
| | | 1/4" x 1/8" | N/A | 33.6 | N/A |
| 14 | 83.8/16.2 | + 3/8" | 1.02 | 33.7 | 13.3 |
| | | 3/8" x 1/8" | 1.26 | 43.4 | 12.4 |
| | | 1/8" x 8M | 1.42 | 48.9 | 11.7 |
| 15 | 91.2/8.3 | + 3/8" | 1.04 | 34.6 | 17.5 |

| | | | | | |
|---|---|---|---|---|---|
| | | 3/8" x 1/8" | 1.02 | 33.7 | 15.3 |
| | | 1/8" x 8M | 1.17 | 40.0 | 11.4 |
| 17 | 94.5/5.0 | + 3/8" | 1.21 | 41.6 | 18.5 |
| | | 3/8" x 1/8" | 1.10 | 37.2 | 28.2 |
| | | 1/8" x 8M | 1.13 | 38.4 | 25.6 |
| 18 | 83.0/7.2 | + 3/8" | 1.16 | 39.6 | 16.1 |
| | | 3/8" x 1/8" | 1.18 | 40.4 | 15.5 |
| | | 1/8" x 8M | 1.19 | 40.8 | 17.1 |
| 23 | 85.7/11.4 | + 3/8" | 0.95 | 30.4 | 23.3 |
| | | 3/8" x 1/8" | 1.13 | 38.4 | 20.6 |
| | | 1/8" x 8M | 1.13 | 38.4 | 13.7 |
| 24 | 86.7/10.3 | + 3/8" | 0.90 | 27.9 | 18.2 |
| | | 3/8" x 1/8" | 1.10 | 37.2 | 19.3 |
| | | 1/8" x 8M | 1.19 | 40.8 | 20.5 |
| 26 | 81.6/12.3 | + 3/8" | 1.03 | 34.1 | 16.1 |
| | | 3/8" x 1/8" | 1.25 | 43.1 | 13.6 |
| | | 1/8" x 8M | 1.42 | 48.9 | 16.0 |

**Table 4. Specifications and Physical Properties of Lightweight Aggregate for Structural Concrete and Masonry Units**

| | Structural Concrete | | | |
|---|---|---|---|---|
| Properties | Coarse | Intermediate | Fine | Masonry Units |
| Size | 3/4" x 4 Mesh | 3/8" x 8 Mesh | 4 Mesh x 0 | 3/8" x 100 Mesh |
| Dry Loose Wt (lb/cu ft) | 40.0 - 50.0 | 40.0 - 55.0 | 54.6 | 45.0 - 58.0 |
| Finess Modulus | 7.00 | 5.61 | 2.72 | 2.78 - 4.38 |
| Specific Gravity | 1.47 - 1.54 | 1.57 - 1.64 | 1.75 - 1.85 | 1.45 - 1.85 |
| Price ($/ton) | 35.0 - 55.0 | 30.0 - 45.0 | 25.0 - 35.0 | 10.0 - 25.0 |

Finess Modulus is the sum of cum. % retained in the sieve analysis divided by 100 for the following sieves: 100, 48, 28, 14, 8, 4, 3/8", 3/4" ,11/2" Tyler Standard Scale

**Table 5. Grading requirements for Typical Lightweight Aggregate for Structural Concrete**

| | 1" | 3/4" | ½" | 3/8" | 4 Mesh | 8 Mesh | 16 Mesh | 50 Mesh | 100 Mesh |
|---|---|---|---|---|---|---|---|---|---|
| ASTM STANDARD C-330 , % Passing | | | | | | | | | |
| Fine Aggregate | | | | | | | | | |
| 4 x 0 Mesh | | | | 100 | 85 - 100 | | 40 - 80 | 10 - 35 | 5 - 25 |
| Coarse Aggregate | | | | | | | | | |
| 1" x 4 Mesh | 95 - 100 | | 25 - 60 | | 0 - 10 | | | | |
| 3/4" x 4 mesh | 100 | 90 - 100 | | 10 - 50 | 0 - 15 | | | | |
| ½" x 4 mesh | | 100 | 90 - 100 | 40 -80 | 0 - 20 | 0 - 10 | | | |
| 3/8" x 8 Mesh | | | 100 | 60 - 100 | 5 - 40 | 0 - 20 | 0 - 10 | | |
| Combined Fine and Coarse Aggregate | | | | | | | | | |
| ½" x 0 | | 100 | 95 - 100 | | 50 - 80 | | | 5-20 | 2-15 |
| 3/8" x 0 | | | 100 | 90 - 100 | 65 - 90 | 35 - 65 | | 10 - 25 | 5 - 15 |