Development and Properties of Foamed Synthetic Lightweight Aggregates

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ABSTRACT

The purpose of this study is to create and evaluate various foamed synthetic lightweight aggregates (FSLA) with a reduced density for the possible use as coarse aggregate replacement within concrete. The synthetic aggregates were foamed utilizing extrusion processes with both chemical and physical foaming agents. The formulations incorporated high carbon fly ash with several different polymer matrix materials. Following the production of the synthetic coarse aggregates, concrete samples were produced using the FSLA as coarse aggregate. The unit weight and compressive strength of these concretes were compared to concrete made with normal weight crushed stone as the coarse aggregate.

The results of the study show that creating FSLA was most successful utilizing physical foaming agents with the twin-screw extrusion process. When incorporated within concrete, test results yield a 20% - 25% lower density and a more ductile failure then those produced with crushed stone. However, this was accompanied with a 65% - 75% reduction in compressive strength.

1.0 Introduction

Recycling of post consumer products has become a growing concern and will only prove to increase in pertinence and popularity as time passes. Since the 1970s, legislation and environmental activists have been pressuring the plastics industry to respond starting with the federal government passing the Resource Conservation and Recovery Act (RCRA).[7] This act introduced a collection method for post consumer bottles by adding a deposit in many states. This was considered a successful step towards a new recycling revolution; although the challenge would become development of efficient ways to reuse these materials.

Plastics make up a rapidly growing portion of the United States municipal solid waste stream (MSW). In 2000, 10.7% of the US MSW was plastics, up from 0.4% in 1960. However, only 5.7% of discarded plastics were recovered (USEPA, 2002). Part of the reason for the low recovery rate of plastics is the wide range of forms in which it occurs. Of the over 41 million metric tons of thermoplastics produced in 2006 in the US and Canada, six types of plastics account for over 70 percent of all plastic sales; polyethylene terephthalate (#1 PETE - 4 percent), high-density polyethylene (#2 HDPE - 14 percent), polyvinyl chloride (#3 PVC - 15 percent), low-density polyethylene (#4

LDPE - 17 percent), polypropylene (#5 PP - 13 percent), and polystyrene (#6 PS - 9 percent). Plastic recycling is difficult because different types of plastic cannot be mixed without compromising the quality of the recycled product.

Fly ash, a coal combustion product (CCP), is one of the byproducts of energy production via coal. The ash byproducts are typically categorized by one of two different types, fly ash and bottom ash. Fly ash makes up 85% of the total residue generated from coal combustion process, leaving the remaining 15% as bottom ash.[6] U.S. power plants produce millions of tons of coal ash every year; of which 35% is used in various applications, leaving the remainder for landfills.[6] Thus, fly ash is a recyclable material where the emphasis must center upon large-volume applications. One potential target for fly ash utilization is the 2-billion-ton per year market for construction aggregate. While most low carbon fly ash produced is can be readily utilized within Portland cement production, high carbon fly ash, which contains carbon content greater then 6%, are not as acceptable in concrete or other pozzolanic applications.[8]

1.1 Objective and Scope

This paper presents the results of a study whose objectives were 1) to develop foamed SLAs (FSLAs) and 2) use these FSLAs in concretes and test the concretes for strength and unit weight. All of the SLAs tested had an approximate fly ash-to-plastic ratios ranging from 0:100 to 70:30. The fly ash used had carbon contents of 10% to 30%. The following presents an overview of the raw materials used in, and the development and manufacturing of FSLAs, and the concrete testing program and results. A discussion of these results and their relevance to low density concretes concludes the paper. The reader is referred to Slabaugh (2006) for more detailed information on the testing program.[18]

2.0 Background

2.1 Porous Polymers / Foams

Many materials naturally contain porous structures; i.e, “bubbles, either discrete or connected, that constitute the major structural form of the overall material. The plastics industry mimics these structures synthetically with the first commercialized foam was introduced in 1908, utilizing phenolic resins under high pressures. Following was latex rubber that was converted to foam rubber around 1914.[14] Today, the understanding of porous polymers is highly evolved and of high interest since such structures typically offer higher strength-to-weight ratios.

2.1.1 Classification of Porous Polymers

Porous polymers maybe classified by cell structure, open cell versus closed cell, and density, high density or low density. The structural integrity is also evaluated and described as either rigid foams or flexible foams, but is usually related to its density. Closed cell structures contain isolated pockets within the polymer that are independent entities. Materials containing closed cells are excellent for applications depending upon high buoyancy, structural rigidity, and thermal isolation. These foams tend to have a superior strength-to-weight ratio compared to open cell structures.[14]

A cell structure that is interconnected allowing for fluids and gas to penetrate are considered open cell structures. These structures are typically weaker and softer then closed cell structures. Applications requiring properties such as good impact, dampening, and absorption would utilize these structures.[14]

The distinction between high and low density is somewhat vague. Both high and low density foams are capable of utilizing an open or closed cell structure. Usually the high-density foams contain closed cell structures and have densities of 75% - 90% of the polymers' solid density. The high-density foams tend to be rigid in nature and are frequently considered as structural foams. The main method of producing high-density foams is injection molding and extrusion processes.

Low-density foams have densities of 10% - 20% of the polymers solid density. These can be described as flexible, but can be rigid and usually utilize an open cell structure. The flexibility mainly will depend upon the polymer used. Unlike high-density foams, the cell structures tend to be more uniform in nature. The majority of the applications for low-density foams are produced with the extrusion process, but many different techniques can be used.[15]

2.1.2 Foaming Agents

Foaming agents, also known as blowing agents, are the key to the formation of the "bubbles" that lead to a porous structure. For polymers, there are two main categories: physical foaming agents and chemical foaming agents. Physical foaming agents typically utilize gas or liquids that are introduced into the system before pressure is released, where the main mechanism is volatilization of gasses to create the porous structure. Possible foaming agents include gases such as nitrogen and carbon dioxide and volatile liquids such as hydrocarbons, partially halogenated chlorofluorocarbons (HCFCs) and fluorocarbons (HCFCs).[16, 17]

Chemical foaming agents (CBAs) typically utilize a solid or powder that decomposes during polymer processes (heating) to create the porous structure. CBAs are preferred over physical foaming agents because they are easer to introduce into a system, do not requiring addition equipment, and usually create a better cell structure and surface finish.[19] The typical dosages for CBAs are small usually only reaching as high as 2% (wt.). However, there must be match between processing temperature and the CBAs decomposition temperature or the agent may work too early (processing temperature too high) or not at all (processing temperature too low).

2.2 Concrete

Concrete is probably one of the oldest formulated materials of which very little has changed. Although as with many naturally occurring creations, synthetic forms were produced and natural concrete is now replaced with concrete made with hydrated cement. Cement is a composite material consisting of predominantly inert materials and other ingredients that creates a state plastic and malleable at first and cures to a hard state.[10]

This composite can contain many different materials and ingredients, but usually consists of a typical generic composition. Within this generic composition the main materials include Portland cement, coarse aggregate, fine aggregate, water, and air.

2.2.1Aggregates within Concrete

Aggregates are defined as materials used within a formulation of concrete for technical and economical reasons. These often are inert granular materials such as sand or gravel that account for approximately three-fourths the total volume of a concrete formulation.[8] The physical properties of aggregates are a very important attribute due to their high volume of the resulting concrete. For the ideal characteristics of aggregates within concrete the particles should be clean, hard, and free of deleterious matter that may ultimately cause the deterioration of concrete.[9] In many ways the aggregates used in concretes dictate the classification of concrete created: low-density concrete, moderate strength or medium density concrete, and structural concrete. Aggregate characteristics that are considered in concrete mixtures include unit weight (or specific gravity), gradation, particle shape and surface texture, and absorption and surface moisture.[9]

For concrete, aggregates are divided into two broad classifications, coarse or fine, as defined by a particle size of 4.56mm (No. 4 US sieve). Because of their larger size, coarse aggregates tend to influence properties such as absorption, surface moisture, particle shape, and surface texture.

2.3 Previous Research on Synthetic Lightweight Aggregates (SLAs)

The uses and applications for fly ash have been a challenge and more importantly a growing interest. The major interest for fly ash is as inexpensive fillers in materials such as composites, polymer formulations, and concrete. These are used in applications such as building materials, polyester mortar, and roads/highways. The most common polymer applications are in Polypropylene (PP), Polyethylene (PE), Polyurethane (PU), and Polyethylene Tarephthalate (PET).[20] Currently, one of the more desirable uses for fly ash is as fillers and/or a component of aggregates used in construction. The development, evaluation and potential applications of synthetic lightweight aggregates (SLAs) have been presented previously in the literature.[1,2,3,4,5] The following outlines two previous studies pertinent to the work presented in this paper.

Shah details a study where high carbon fly ash (HCFA) is used as a filler in various thermoplastics. The main objective of his study was to compound and establish quantifiable values of physical properties with HCFA in various polymer matrixes; ultimately producing successful formulations incorporating high filler contents (50% - 80% by weight). The results of this study showed that an increase in HCFA content would increase the bending modulus while lowering the ductility of the materials as indicated by the outer fiber strain at break.[11]

A study presented by Malloy etal (2001) compared concrete made with traditional expanded clay/shale aggregate to concretes made with synthetic lightweight aggregate (SLA). Various SLAs were produced by melt compounding high concentrations of high carbon fly ash (HCFA) with two thermoplastic formulations: 1) pure HDPE and 2) a mixed plastic (MP) formulation consisting of a combination of PET, HDPE, LDPE, PP, and PS. Evaluation of these SLAs found that their aggregate properties are influenced by both the concentration of HCFA and the thermoplastic formulation utilized. However, the effect the thermoplastic on the properties of the aggregate decreases as the concentration of HCFA increases, becoming almost inconsequential as HCFA content reaches 80%. Therefore, the various thermoplastic binders were very similar, proving the mixed thermoplastic formulation to be a strong candidate for the use as a binder within the SLA.[13]

Concretes were developed with these various SLAs and tested for strength. These results were compared to a concrete created with expanded clay/shale lightweight aggregate. All concretes had similar fine aggregate (ASTM C-33 sand) and water-to-cement ratio (0.5), yet different coarse aggregates were used including different SLAs and expanded clay/shale aggregate. The result from the compression test of the concrete samples can be found in Table 1. The results showed that the lightweight concrete produced using the HCFA/mixed thermoplastic binder coarse aggregate showed sufficient compressive strengths for use as structural concrete (> 17 MPa), although these strengths were significantly lower than the concrete containing expanded clay/shale coarse aggregate (approximately 42 MPa). Additionally, SLA-based concretes exhibited a more ductile behavior than the samples produced with expanded clay/shale. Therefore, the SLAs produced using thermoplastic binders and HCFA can provide adequate properties when used in concrete.[13]

Table 1 Lightweight Concrete Compression Test Results[13]

Coarse Aggregate Type	Compressive Strength (MPa)
Expanded Clay/Shale	42 ± 1
Pure HDPE Aggregate	14 ± 1
80:20 SLAHDPE (SLA made with 20% HDPE and 80% HCFA	20 ± 1
80:20 SLAMP (SLA made with 20% MP and 80% HCFA	22 ± 1

3.0 Materials and Procedures

This study represents a continuation of other studies produced with the intention of creating a new synthetic lightweight aggregate for use within lightweight concrete for building construction applications.[11,12,13] A number of coarse-sized SLAs (i.e., particles sizes > 4.56 mm) were developed with HCFA concentrations of 0%, 10%, 30%, 50%, and 70% (by weight). The fly ash used in this study, obtained from a coal combustion facility in the northeastern U.S., was the discarded ash from a beneficiation process that separates low carbon (<6% by weight) from high carbon fly ash. The typical carbon content of the fly ash ranged from 15 to 30%.

3.1 Manufacturing Process

The synthetic lightweight aggregates used in this study were created by combining fly ash and plastics though a melt blending process. The compounding was performed in a co-rotating intermeshing twin screw extruder at mixing temperatures between 200 and 230 °C. Typically, during the mixing process, plastic polymers are fed into the primary auger feeder and fly ash is added through a downstream feeder to obtain the desired fly ash-to-plastic ratio. The mixing product is extruded, quenched in a water bath to cool, and solidified. The solid extrudate is then granulated in a rotating knife granulator to produce SLA particles. Particles are dark-gray to black in color and range in texture from firm to noticeably deformable, depending on the type of plastic used.

In addition to traditional SLA production, foamed SLAs (FSLA) were produced using nitrogen (N_2), a physical foaming agent, in the twin-screw extrusion process. The various HCFA contents of the FSLAs were similar to that of the SLAs so as to compare the effectiveness of the blowing agent with various fly ash concentrations. Since all SLAs and FSLAs have nearly identical grain size distributions, the only physical variable was HCFA content and whether or not a blowing agent was used.

Aggregate properties evaluated in this study included specific gravity, apparent or bulk density, and water absorption. Tests for specific gravities were performed in accordance with ASTM D 792-00. The apparent density was measured for all SLAs in accordance ASTM D 1895-96. The water absorption values were determined for all SLAs with guidance from ASTM C 127 standard.

3.2 Concrete Development

Concretes containing these various SLA and FSLA were produced and tested with results compared to a “control” concrete containing the normal weight crushed stone aggregate (with a similar grain size distribution). The cement used for this study was a Portland cement Type I/II manufactured by Dragon Products Company. The fine aggregate used normal weight sand meeting the requirements of ASTM C-33. For all concretes a 50/50 mixture by volume of coarse and fine aggregates were used. Since the concretes produced to evaluate the effect of the different density coarse aggregates, the concretes were created with equivalent volumes of cement, fine aggregate, and coarse aggregate; thus the same weight of cement and fine aggregate was used in all concretes. Concrete mix proportions are presented in Table 2.

For all concrete mixes, the aggregates were measured, weighed, and mixed dry. Upon mixing with water, slump tests, in accordance with ASTM C 143-74, were performed to determine the consistency and workability of the fresh concretes. All concretes were mixed to a slump of 8.9 ± 1.27cm (except the FSLA with 70% HCFA which was mistakenly made too wet). The amount of water added to achieve this range of slump for each is presented in Table 2. Three cylindrical specimens, 10.2 cm diameter by 20.3 cm high, were created for each concrete. Specimens were cured for 28 days in a high humidity room (relative humidity > 85%) until tested for 28-day compressive strength. The eleven samples including their water content and slump values are presented in Table 2.

3.3 Compression Testing

For compression tests, a Forney (Model # F96) 250k load frame was used. Specimens were tested at a constant load rate. The goal for this study was to utilize a peak compression rate between 200 – 300 lb/sec. Peak compression rates along with the maximum compressive load of test specimens were recorded.

4.0 Test Results and Discussion

4.1 Aggregate Properties

Aggregate properties of both the SLA and FSLA determined during the study included the specific gravity, apparent or bulk density, and water absorption. Results for these tests are reported in Table 3. These tests allow the effects of the “new voids” in

Table 2 Concrete Mix Proportions and Fresh Concrete Slump Values						
Coarse Aggregate Description*	Cement (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Total Aggregate (kg)	Water (kg)	Slump (cm)
Crushed Stone	3.59	6.23	5.68	11.91	1.64	9.53
70:30 SLA No BA	3.59	6.23	1.45	7.68	1.64	8.89
70:30 FSLA w/N2	3.59	6.23	1.86	8.09	1.77	17.78
50:50 SLA No BA	3.59	6.23	1.05	7.27	1.68	7.62
50:50 FSLA w/N2	3.59	6.23	1.27	7.50	1.73	8.89
30:70 SLA No BA	3.59	6.23	1.36	7.59	1.68	10.16
30:70 FSLA w/N2	3.59	6.23	0.64	6.86	1.73	8.89
10:90 SLA No BA	3.59	6.23	1.41	7.64	1.73	8.89
10:90 FSLA w/N2	3.59	6.23	0.45	6.68	1.77	7.62
0:100 SLA No BA	3.59	6.23	1.55	7.77	1.59	8.26
0:100 FSLA w/N2	3.59	6.23	0.45	6.68	1.77	9.53
*Note: No BA indicates no blowing agent, N2 indicates nitrogen as blowing agent						

the porous structure to be evaluated. Two trends in results are noticeable. At low HCFA contents (< 30%) both the specific gravity and bulk density of FSLAs are lower than there SLA counterpart and the water absorption values are higher for FSLAs than SLAs. It is clear that a porous structure has been formed at these lower HCFA contents. However, at HCFA content of 50%, FSLAs and SLAs have similar values of specific gravity and bulk density and the water absorption value of FSLAs is now slightly lower than that of SLAs. At HCFA of 70%, the values for all properties are about equal. Taken together, these results indicate that the foaming of SLA with nitrogen was very effective at low fly ash contents, but not as effective at HCFA contents at or above 50%. Though all aggregates have similar grain size distributions, it can be hypothesized that other factors such as particle shape and angularity also play an important role in the value of the bulk density.

4.2 Concrete Properties

The various concretes were evaluated for unit weight and strength. These results are compared to a concrete containing crushed stone coarse aggregate. Test results are presented in Table 4. Observations of the type of failure that occurred during testing highlight the differences between SLA and the crushed stone concrete. Samples containing crushed stone showed a higher load rate that quickly reached and maintained a steady value until reaching the peak stress. Upon reaching the peak, the load would suddenly drop (creating a negative load rate), and the sample would collapse into separable pieces. Alternatively, SLA and FSLA samples had lower load rates that would slowly increase and then remained constant. Upon reaching the maximum load, the load rate would decrease but at a much slower rate than the crushed stone. Additionally, the SLA and FSLA samples remained intact, only exhibiting. This observed behavior is indicative of a more ductile response as well as a potential for SLA and FSLA concretes to have an ability to absorb energy during compression.

Table 3 Summary of Aggregate Properties for SLAs and FSLAs

Coarse Aggregate Description*	Specific Gravity (ASTM 792)	Bulk Density (kg/cm^3)	Absorption (%)
70:30 SLA No BA	0.96	0.37	2.15
70:30 FSLA w/N2	1.04	0.47	2.13
50:50 SLA No BA	0.77	0.26	5.60
50:50 FSLA w/N2	0.82	0.31	2.76
30:70 SLA No BA	0.88	0.35	2.28
30:70 FSLA w/N2	0.38	0.16	8.57
10:90 SLA No BA	0.87	0.34	2.28
10:90 FSLA w/N2	0.32	0.11	8.50
0:100 SLA No BA	0.92	0.39	1.39
0:100 FSLA w/N2	0.30	0.11	13.22
*Note: No BA indicates no blowing agent, N2 indicates nitrogen as blowing agent			

Table 4 Summary of Concrete Results for SLAs, FSLAs and Crushed Stone

Coarse Aggregate Description*	Unit Weight (kN/m^3)	Compressive Strength (MPa)	Load Rate (kN/sec)
Crushed Stone	23.7	39.9	1.5
70:30 SLA No BA	18.5	13.6	1.2
70:30 FSLA w/N2	18.3	12.3	1.0
50:50 SLA No BA	18.8	12.6	1.1
50:50 FSLA w/N2	18.3	12.1	1.1
30:70 SLA No BA	18.1	11.2	1.0
30:70 FSLA w/N2	18.0	11.1	1.0
10:90 SLA No BA	18.3	11.4	1.1
10:90 FSLA w/N2	17.6	10.3	0.9
0:100 SLA No BA	18.2	11.1	1.1
0:100 FSLA w/N2	17.6	10.1	0.8

Based on the comparison of there is an affect of using FSLA versus SLA in concrete. The result in Table 4 show that FSLA concretes have up to about a 4% decrease in sample unit weight while also yielding up to about 10% decrease in compressive strength compared to regular SLA. This suggests and supports the long established relationship between sample unit weight and compressive strength.[21] Therefore, it can be stated that decreasing the unit weight of the concrete, via increasing porosity of the aggregate, will also decrease its compressive strength.

When compared to crushed stone concrete, all SLA and FSLA concretes produced created a data population that yields about 20% - 25% lower unit weight. However, this reduction in unit weight is associated with about a 65% - 75% lower compressive strength than that of the crushed stone. However, one must consider the difference in load rate when evaluating the relatively large difference between the crushed stone samples and the SLA / FSLA samples. Since, in general, crushed stone samples had a higher loading rate than the SLA / FSLA samples, its strengths will be inherently higher. However, even if corrected, this difference in strength will still remain. Despite of the strength decrease, SLA / FSLA concretes do show reasonable strengths appropriate for some applications, such as sidewalks.

5.0 Summary, Conclusions, and Recommendations

The scope of this work was to investigate the feasibility of creating a foamed synthetic lightweight aggregates (FSLAs), defining the properties of these aggregates along with the properties of concretes containing coarse-size particles. A physical blowing agents, nitrogen gas, was used on a recycled mixed thermoplastic formulation (MP) of SLA at high carbon contents of 0, 10, 30, 50 and 70% (by weight).

The results indicate that the amount of foaming tended to decrease as filler content increased. As the filler concentration approached 50% filled, foaming was somewhat nullified, possibly having negative effects.

All concrete samples containing the SLA and FSLA coarse aggregates yield about a 20% - 25% lower density than that of those produced with a crushed stone coarse aggregate. Consequently the results also show about a 65% - 75% lower compressive strength then that of the crushed stone. Despite the large difference between crushed stone and the SLA / FSLA concretes, the compression strength values still ranged between 9650 – 13780 kPa while failing in an intact state; portraying a more ductile behavior. Due to the failure properties of these concrete samples, the ductile behavior may result in possible useful properties for specific applications. The authors recommend that future work evaluate the effects on concretes that utilize the FSLAs at different levels of coarse aggregate content (< 100%).

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