

CHELSEA CENTER FOR RECYCLING AND ECONOMIC DEVELOPMENT

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**FLY ASH/PLASTIC SYNTHETIC AGGREGATE
FOR CONSTRUCTION MATERIAL**

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FLY ASH/PLASTIC SYNTHETIC AGGREGATE FOR CONSTRUCTION MATERIAL

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The Chelsea Center for Recycling and Economic Development, a part of the University of Massachusetts' Center for Environmentally Appropriate Materials, was created by the Commonwealth of Massachusetts in 1995 to create jobs, support recycling efforts, and help the economy and the environment by increasing the use of recyclables by manufacturers. The mission of the Chelsea Center is to develop an infrastructure for a sustainable materials economy in Massachusetts, where businesses will thrive that rely on locally discarded goods as their feedstock and that minimize pressure on the environment by reducing waste, pollution, dependence on virgin materials, and dependence on disposal facilities. Further information can be obtained by writing the Chelsea Center for Recycling and Economic Development, 80 Everett Avenue, Chelsea, MA 02150.

EXECUTIVE SUMMARY

Synthetic Lightweight Aggregate (SLA) was developed and evaluated for use in construction applications such as concrete masonry units (CMU), lightweight concrete, and asphalt pavement. The SLA is produced by melt compounding commingled waste plastics and high amounts of fly ash. The plastics used in this study are type 3 through 7 (i.e., types 3,4,5,6, &7) waste plastics from municipal solid waste streams and the fly ash is residue from coal burning power-generating plants. Both of these materials are disposed in landfills through out the US and elsewhere in the world in large quantities.

In this study, a series of lightweight aggregate samples were produced using ammoniated fly ash and waste plastics from computer housings. The ammoniated fly ash is produced by coal burning power plants that are in compliance with recent requirements by the federal government to lower their NO_x and SO_x emissions into atmosphere. The results of this study show that the presence of ammonia in fly ash has no impact on the production process of SLA and no ammonia was released during the melt compounding of ammoniated fly ash and commingled waste plastics at the ratio of 80:20 fly ash to waste plastics.

The study also showed that waste plastics from other sources than municipal solid waste can be used to produce SLA. The SLA produced using waste plastics from computer housing did not impact the production process and the final product and the SLA was similar to the ones produced using mixed-waste plastics from municipal solid waste.

The effect of PVC (polyvinyl chloride plastics) in the waste plastic stream was also tested and the results indicated that at practically any ratio, the PVC degrades at the high temperature required for producing SLA and therefore the HCl gas that is emitted may be corrosive to the production equipment and may be harmful to workers without controls. Without proper measures to control the emission of HCl, use of more than 4% PVC in the production of SLA should be avoided.

Several SLA samples that were produced from various fly ash-to-plastic ratios were tested for bulk unit weight, specific gravity, and absorption potential. It was concluded that the bulk specific gravity and absorption capacities of the SLA generally increase as the fly ash content of the SLA increases.

The SLA samples were also tested for Los Angeles Abrasion. The SLA with 80% fly ash outperformed every other aggregate tested in this study for comparison. This test is very crucial test for use of aggregate in asphalt pavement and results show high potential for use of SLA in asphalt pavements.

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1.0 INTRODUCTION

Industrial manufacturing can be simplified into a set of processes, which directly or indirectly utilize material resources to create final products. Some examples include the use of coal by utilities to produce electricity and the use of crude oil to form the basis of gasoline, heating oil, and plastics. However, waste materials are inevitably produced in the manufacturing process or from post consumer waste. These wastes, depending on their nature, must be handled and disposed of properly, though such a strategy for final material management is highly insufficient. A more efficient system would minimize both the input of limited resources and the output of waste material (Figure 1). If waste creation can be reduced through more efficient production and waste disposal can be reduced via recycling and reuse (of manufacturing by-products and post-consumer products), the entire system will become significantly more efficient and sustainable as less raw materials are required and less wastes are disposed of.

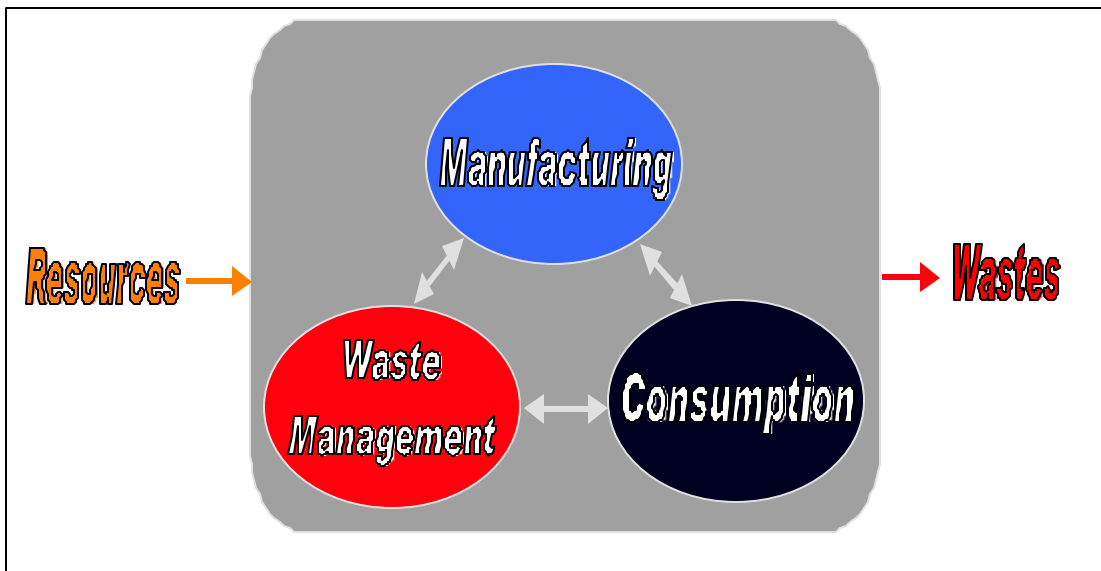


Figure 1. Resource and Waste Optimization process

As available space within landfills decrease, worldwide recycling programs are being established and expanded. These include both collection and separation programs but also the production of new products from these secondary (waste) materials. The construction industry is a logical choice for the potential reuse of manufactured by-products and post consumer materials due to the large quantity of construction materials that are used every year.

The recycling of two high volume secondary materials, waste plastics and coal fly ash, into a new product is the goal of this study. Both of these waste materials are produced in very large amounts. The current volume of plastics recycled is much less than what is being landfilled. Only a small percentage (less than 20%) of coal fly ash is being used as

beneficial additives to concrete (e.g., coal fly ash is used in concrete to replace a portion of cement and/or as a mineral admixture to improve several properties of concrete such as strength, reduced permeability, and durability). However, the fly ash used in concrete must pass a very strict standard as defined by ASTM C618¹ for carbon content (less than 6%) and the majority of fly ash produced does not meet this standard.

The proposed new product to be made from waste plastics and coal fly ash is a synthetic granular material that can substitute for natural lightweight and normal weight aggregates used in making various building materials, thereby conserving the natural resources that are mined for aggregates and also reducing required landfill space.

2.0 RESEARCH OBJECTIVES

The objectives of this research were to:

1. Produce a synthetic lightweight aggregate using large volumes of coal fly ash and post-consumer and post-industrial waste plastics;
2. Produce a synthetic lightweight aggregate containing the maximum amount of fly ash as possible and using the least desirable fly ash sources;
3. Evaluate physical and engineering properties of the aggregates;
4. Investigate the aggregates' potential for use in construction materials such as Portland cement concrete, asphalt (bituminous concrete), and geotechnical fill.

The synthetic lightweight aggregate presented here forth has the potential for utilizing large volumes of fly ash containing high carbon and ammonia which makes it unsuitable for standard, direct use in concrete as a mineral additive or Portland cement replacement.

3.0 PROJECT JUSTIFICATION

This work is part of an attempt to develop a new commercial product from two secondary (waste) materials: 1) coal fly ash and 2) #3-7 mixed waste plastics. Except for small percentages that are recycled, most of both of these materials are currently sent to solid waste disposal facilities (landfills) in the Commonwealth of Massachusetts and elsewhere. The proposed product, a synthetic lightweight aggregate, is a granular material that could be used in the construction industry for lightweight geotechnical fill, manufacturing of pre-cast concrete elements such as masonry blocks and other structural elements, construction of roads and pavements, as well as lightweight geotechnical fill.

3.1 Fly Ash

In general, ash is a finely divided residue produced from coal combustion as well as other thermal processes (e.g., municipal solid waste and soil incineration). From coal burning power plants, 108 million tons of Coal Combustion By-products (CCBs) are produced in the United States each year; 63 million tons of which is fly ash². Presently, only 29% of the CCBs produced annually are recycled, the remaining material is typically disposed of in landfills. With tighter restrictions on NO_x emissions imposed by the implementation of the 1990 Clean Air Act Amendment, less desirable CCBs containing higher levels of unburned carbon and sulfur as well as ammonia compounds will result³. Annual costs for the disposal of CCBs are approximately \$1 billion; a figure that will surely rise as available landfill space diminishes, the amount of harmful constituents in the fly ash increases, or environmental regulations become stricter. Finding possible uses for large quantities of CCBs that can tolerate variance in CCB composition is becoming vital for environmentally sustainable development.

Only about 1/6 (17%) of coal fly ash is presently utilized in the construction industry, and this is by far the largest single reuse market for CCBs. The most widespread application for coal ash has been and continues to be for cement replacement in ready-mix concrete provided it meets strict quality criteria such as consistency and low carbon content.








3.2 Recycled Plastics

Annually, the need for more plastic recycling becomes more important due to the continuing expansion of the plastics industry and growing public concern over the use and disposal of plastics. The annual consumption of plastic in the United States is nearly five times greater today than it was in 1970⁴. It is estimated that in the U.S. alone, 40 million tons of plastics were used in product manufacturing in 1998⁴. Unfortunately, the recycling rates for plastics have not kept pace with the increased level of production. As a result, waste plastic packaging and durable products represent a significant portion of the Municipal Solid Waste (MSW) stream. While the weight percentage of plastic entering the MSW stream is relatively low, the volume percentage is as high as 20% due to the low specific gravity of most plastics and the bulky shape of many plastic products⁴.

By 1998, 80% of the communities in the United States had initiated plastics recycling programs of some kind. Between 1986 and 1998, the number of plastic recycling companies increased from 310 to a total of 1792⁵. However, the volume of waste plastics generated far exceeds the capabilities or demand of the current plastics recycling industry.

Most plastics, specifically all thermoplastics, can be “mechanically” recycled if properly separated to different resin types. To aid both recyclers and consumers for separating different resins, the Plastic Bottle Institute initiated a bottle coding system in 1988. The codes were adapted by the Society of the Plastic Industry (SPI) Table 1.

Table 1: Society of the Plastics Industry (SPI) Resin Coding System⁷

Resin	SPI Code	Letters	Resin Types	Examples
#1	 PETE	PET (PETE)	Polyethylene Terephthalate	2-liter Soda Bottles, Some Condiment Containers
#2	 HDPE	HDPE	High Density Polyethylene	Milk Jugs, Laundry Detergent Containers
#3	 V	PVC	Vinyl/Polyvinyl Chloride	Some Drinking Water, Vegetable Oil Containers
#4	 LDPE	LDPE	Low Density Polyethylene	Flexible Film Bags, Flexible Lids, Plastic Bags
#5	 PP	PP	Polypropylene	Jar Lids, Container Closures, Battery Cases, Box Liners, Some Bottles
#6	 PS	PS HIPS	Polystyrene High impact Polystyrene	Fast Food Foam Boxes, Foam Cups, Meat Trays, Computer housing
#7	 OTHER	OTHER	-	Multiple Resin Materials, Some Squeezable Containers

The recycling infrastructure for both polyethylene terephthalate (PET) and high-density polyethylene (HDPE) containers are fairly well established. The limited rates of recycling for other thermoplastics (i.e., #3-7) are more of an economic rather than a technical impediment issue. The costs of separation, cleaning, transportation and reprocessing the waste plastic limits the economic reuse of the theoretically recyclable materials⁶. The economics of plastic collection and recycling are greatly improved if the “degree” of separation and cleaning for the waste plastic can be minimized. It is hoped and expected that plastic recycling processes in the near future (depending on the products to be made) will be more tolerant to both material composition variation and cleanliness, and as a result will be more economically attractive⁵.

3.3 Aggregate

According to statistics compiled by the U.S. Bureau of Mines, the United States produces about 2.1 billion tons of aggregate⁸. The construction industry is the greatest consumer of aggregates in the world. Aggregates are used in the manufacture of Portland cement concrete, bituminous (asphalt) concrete, plaster, grout, filter beds, railroad ballast, base course for roads, building foundation sub-base, and drainage fill.

Aggregates are a rocklike material of random size and shape. They are found in nature as sand, gravel, stones, or rock that can be crushed into smaller sized particles. ASTM C128⁹ and D8¹⁰ define aggregate as a granular material such as sand, gravel, crushed stone, or iron-blast-furnace slag used with a cementing medium to form mortar or concrete, or alone as base-course fill.

Most of these sand and gravel aggregates have a relatively high density. Lightweight aggregate is made by expanding shale and other minerals with heat to form a less dense material that is still hard enough to be used in concrete and for other uses.

3.4 Past Research

In the previously funded phase of this project (Fiscal Year 2001 grant from the Chelsea Center which is, available on the Chelsea Center’s website, <http://www.chelseacenter.org/TechReptsDesc.htm#35>, as Technical Report #35, “Development of Synthetic Lightweight Aggregate for Construction Material”) we produced synthetic lightweight aggregate from both homogeneous and mixed thermoplastic waste sources. The homogeneous thermoplastics (LDPE, HDPE, and PS) were utilized in an effort to learn how the plastic binder stiffness affects the performance of the thermoplastic/fly ash aggregate. In an effort to show that mixed plastic waste and fly ash can serve as the feedstock for synthetic lightweight aggregate, a mixed plastic binder formulation was also utilized. An 80/20 fly ash/thermoplastic aggregate was produced using a mixed plastic stream typical of #3 –7 post consumer wastes. The production process is shown schematically in Figure 2.

A clean, largely recycled formulation containing a mixture of PET, HDPE, LDPE, PP, PS, and HIPS polymers was used for aggregate production with very good success.

There are few, if any, plastic products that can be made using combination of multiple polymers together without using compatibilizing agents. However, this test was conducted in large part to show that the synthetic aggregate process is less critical than most conventional thermoplastic processes in terms of material viscosity and process stability and final product integrity. The aggregate properties are more dependent on fly ash concentration than thermoplastic composition at such high fly ash concentrations (e.g. 80% fly ash)

The synthetic lightweight aggregate was tested for physical and chemical properties. Several concrete cylinders made with the synthetic lightweight aggregate and their characteristics were comparable in properties with those of ordinary lightweight aggregate available in the market.

Using a cement/aggregate mixture ratio suitable for concrete masonry blocks, several concrete masonry blocks were made in the lab using a plywood mold. Both lightweight aggregate and SLA were used in the mixes and several cylinders cast from these mixes were also tested for compressive strength at various ages. Test results (see CCFRED Technical Report # 35) indicated that the SLA is suitable to be used in concrete masonry units (CMU).

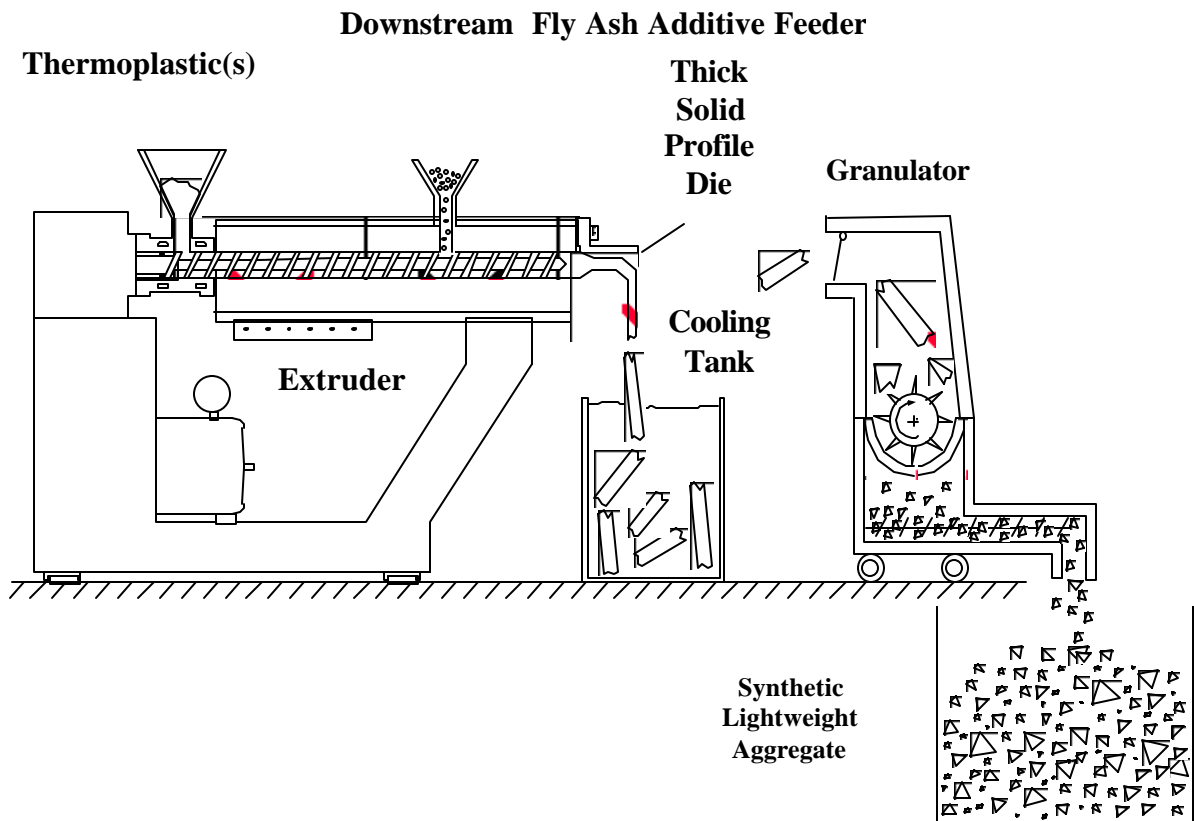


Figure 2. Production Process of SLA

4.0 SCOPE OF WORK

This report presents the results of the second phase of a study conducted on the development and use of synthetic lightweight aggregate made with waste plastics and fly ash. The study was also funded by the Chelsea Center (Fiscal Year 2001) and concentrated on the following tasks

4.1 Determining the Effect of PVC Content in the #3-7 Plastic Waste Streams

The mixed plastics used up to this point to produce SLA did not contain polyvinyl chloride (PVC). While PVC is one of the two most widely used thermoplastics, it was not included in the previous mixed plastic model studies for two specific reasons. First, PVC is not found in high concentrations in the post consumer household packaging waste stream (bottles, rigid containers etc.). PVC (both flexible and rigid) is mostly used in items such as vinyl siding, window profiles, wire coating, plastic piping, flooring, furniture, pool liners, hoses, and many more durable good type applications. PVC is used for certain types of consumer packaging, such as transparent “blister” (thermoformed) packaging and some bottles/containers, but its concentration in the post consumer waste stream is relatively low.

A second issue associated with using PVC scrap in the manufacturing of SLA is the relatively high processing temperature of SLA. Like most of the other plastics in the mixed stream described above, PVC has a relatively low processing temperature. PVC is normally melt-processed at temperatures in the 170 to 205°C ranges. However, unlike the other lower melting temperature thermoplastics listed above, PVC has a narrow processing temperature window. Specifically, rapid de-polymerization or degradation will occur if PVC is exposed to temperatures above 210°C for a period of time. PVC monomer consists of a carbon-carbon double bond and a single chlorine atom and three hydrogen atoms. As PVC degrades, the chlorine atoms along with the hydrogen atoms are released together in the form of HCL gas, which produces hydrochloric acid when combined with water. Therefore, PVC was purposely excluded from the model mixed plastic formulation in order to avoid the anticipated generation of HCL gas that may cause corrosion of the processing equipment. However, since PVC is likely to be found in some mixed plastic waste streams, a study to determine the effect that PVC has on SLA production was initiated.

4.2 Alternative Thermoplastic Waste Streams

There are a number of other waste thermoplastic sources (other than what traditionally is found in the municipal solid waste stream) that could also potentially be utilized in the manufacturing of SLA. In recent years, large quantities of electronic appliance plastic waste have entered the post consumer waste stream. According to the American Plastics Council¹¹ a variety of plastic polymeric resins are used in the manufacture of electronic equipment (Figure 3). However, the market for post consumer electronic business machine plastics is not yet very well established.

Plastic items recovered from business machine dismantling operations include computer monitor cases, CPU housings, television cabinets, photocopier components and the like. Almost all of these parts are made with some type of thermoplastic, and as such should be recyclable. Unfortunately, a wide variety of plastics are used for these components and segregation is costly. In addition, many of these items are contaminated with electromagnetic interference (EMI) coatings, labels, and other contamination. When used as a commingled plastic waste stream, the properties of the commingled plastic blend are usually quite limited, specifically exhibiting a very low breaking strain and impact resistance. This greatly limits the use of mixed electronic plastics for conventional secondary recycling applications. However, it is likely that these mixed plastics could be used for SLA production since this application has been shown to be relatively insensitive to the mixed plastic composition.

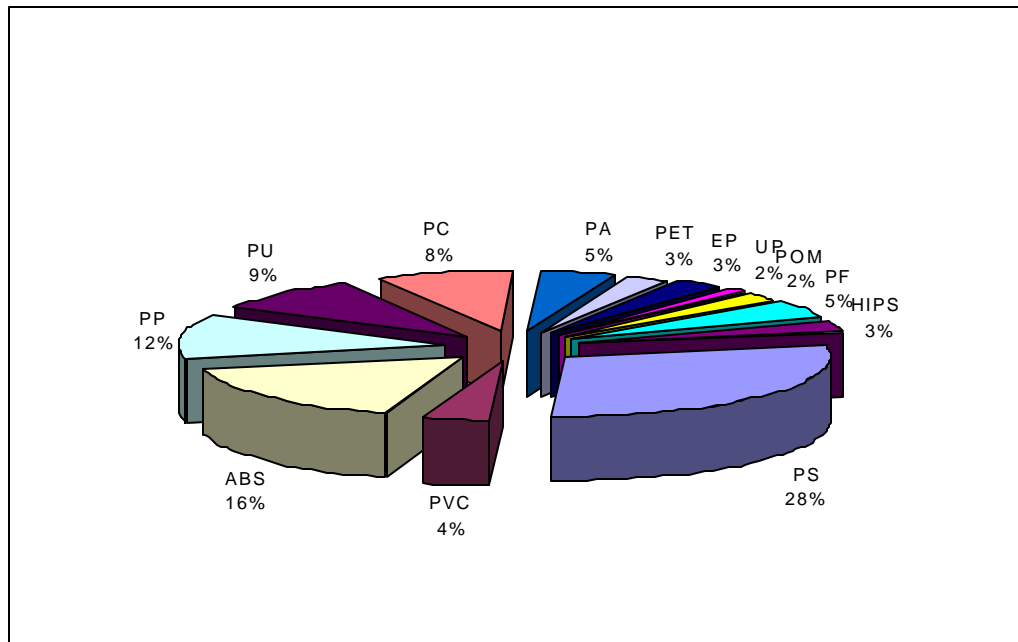


Figure 3. Plastic Resins Used in Electronic Equipments¹¹

4.3 Use of Ammoniated Fly Ash for Producing SLA

Recent Environmental Protection Agency (EPA) Clean Air Act amendments mandated that the reduction in emissions of NO_x from coal fired power-generating facilities in the states east of the Mississippi. With the exception of Florida, Maine and Vermont, facilities are required to meet NO_x emissions of 0.15 lbs./ mmBTU. In order to meet the new NO_x emission requirement, many utilities will use a combination of combustion management and post combustion processes. Combustion management techniques include low NO_x burners, over fired air systems, reburning and flue gas recirculation. The most commonly used combustion management technique is low NO_x burners. Low NO_x burners contribute to higher residual carbon levels in the resulting fly ash.

Therefore there will be more high carbon fly ash produced that cannot be used in concrete production.

Post-combustion processes use ammonia in the conversion reaction of NO_x to nitrogen and water. Post-combustion NO_x controls result in a certain level of inefficiency in regards to the ammonia reducing process. This inefficiency results in fugitive ammonia emissions called ammonia slip. Ammonia slip results in a significant portion of ammonia being deposited on the fly ash. European data indicates that combustion of coal in the 6–8% ash range with slip values of 2 ppmv (part per million by volume) in the flue gas result in concentrations of approximately 100 ppmw of ammonia on fly ash. This example indicates that approximately one third of the ammonia slip “reports” to the fly ash. Currently, little documentation exists as to the amount of ammonia residues found on fly ash resulting from NO_x reduction operations. It has been reported that low NO_x operations can produce ammonia concentrations in fly ash in the thousand-ppmv range.

So these NO_x control technologies will result in increased levels of carbon and ammonia in fly ash. The ASTM C618 specification for concrete limits LOI (loss of free carbon on ignition) to 6%, largely because the higher LOI levels often result in discoloration and poor performance of chemical additives such as air entrainment agents (AEA) and plasticizers used in making concrete. AEA are used to stabilize the small air bubbles, which provide freeze-thaw resistance in concrete. In the case of using ammoniated fly ash in concrete, ammonia will be released from fresh concrete due to the high pH of Portland cement (ammonia stripping). In addition to the harmful effect that ammonia could have on the concrete workers during mixing and placing, its impact on other properties of concrete is yet to be studied.

In fact, use of NO_x control technologies may result in once-marketable fly ash becoming unusable and destined for disposal. Ammonia contaminated fly ash will also result in re-evaluation of landfill disposal practices. Ammonia residues found on fly ash is highly water-soluble and have the potential to contaminate both ground and surface waters.

4.4 Engineering Properties of SLA

In our original proposal for this study, we proposed to manufacture sufficient quantities of SLA in the lab so that a local concrete masonry unit (CMU) manufacturer could manufacture several CMUs as a pilot production study. However, after producing more than 500 lbs. of SLA in the laboratory of the Plastic Engineering Dept. at the University of Massachusetts Lowell, we realized that production of the minimum amount of SLA required for a meaningful CMU manufacturing study was beyond the capacity of the lab scale extruder we were using. Samples of SLA made in the lab were tested for engineering properties such as unit weight, specific gravity, and Los Angeles abrasion test that we did not perform in the previous phase of this project.

5.0 EXPERIMENTAL STUDIES

5.1 Previous Mixed Waste Composition

In the previous phase of this study (see Chelsea Center Technical Report #35), it was demonstrated that SLA can be produced using “mixed waste plastic” as a matrix or binder for both high and low carbon fly ash. A number of mixed plastic formulations were evaluated, however, most of the studies were conducted using the following mixed plastic formulation.

30%	PET (recycled injection blow molding grade)
30%	HDPE (recycled blow molding grade homopolymer)
5%	HDPE (injection molding grade)
10%	LDPE (blow film extrusion grade)
10%	PP (injection molding grade)
5%	PS (injection molding grade)
10%	HIPS (injection molding grade)

This blend of plastics is typical of plastics collected from residential solid wastes and processed by Material Recycling Facilities (MRFs). This combination was used in this study based on the results of our earlier study on a bale of type 3 – 7 waste plastics after plastic types 1 and 2 were removed by a local MRF. The contents of the bale were determined item by item. Surprisingly, the bale still contained about 30% PET (#1) and 30% HDPE (#2). These items were somehow slipped through the separation system or were purposely rejected due to a number of possible reasons such as contamination, multiple layers of different resins, color, and etc.

Without further separation, such commingled plastic waste, has little, if any, use presently as a feed material for most plastic manufacturing processes. Such a mixture of commingled plastic is relatively difficult to process and the final product will have very low breaking strains hardly usable in traditional plastic products. However, this mixed blend proved to be useful as a binder for SLA for two primary reasons.

1. The quality of the final product (SLA) is not significantly affected by processing (melt extrusion) problems such as surging or out-gassing.
2. The breaking strains for cement type products are significantly lower than those of a SLA made with this mixed plastic formulation. The breaking strains are low by plastic standards, but not relative to normal or other lightweight aggregate or concrete.

The mixed plastic formulation listed above is comprised of plastics that have very different processing temperatures. Table 2 shows the melting temperature for various plastic resins. For example, PET is normally melt-processed at a temperature in the range of 270 to 280°C. PET has a relatively narrow processing window and melting will not occur if the material is processed at lower temperatures. In general PET represents a very

significant percentage of the (mixed) post-consumer plastic waste stream. The processing temperature for mixed plastics is dictated by this high melting temperature material (if all thermoplastic components are to be melted). A temperature of 270°C has been found to be sufficient for this purpose. However, most of the other thermoplastics in the mixed plastic formulations are normally processed at a much lower temperature, generally in the range from 175 to 230°C, depending on the specific material.

While 270°C is well above the normal processing temperature of these materials, the other thermoplastics in the mixture (HDPE, LDPE, PS and HIPS) do have relatively wide processing temperature windows. Some degree of thermal degradation is still quite likely. However, the relatively crude nature of both the compounding process and product (SLA) will minimize any degradation related problems. For example, the discoloration normally associated with molecular degradation is not evident since the SLA product is naturally dark or black in color. The off gassing associated with degradation is not a problem since a limited amount of foaming or porosity in SLA is acceptable. There is a significant odor problem occurring at the extruder discharge point, which is most likely associated with the butadiene component in the HIPS. However, the conventional ventilation or exhaust systems used for plastic processing equipment should prove to be adequate in this respect.

Table 2: Melting Temperatures of Different Plastic Resins

Polymer Resin Type	T_m (° C)
High-Density Polyethylene (HDPE)	128-135
Low-Density Polyethylene (LDPE)	102-112
Polystyrene (PS)	242
Polyethylene Terephthalate (PET)	270
Polypropylene (PP)	121
High-Impact Polystyrene (HIPS)	85

5.2 Test Results from of the Effect of PVC

As mentioned in 4.1, the mixed waste plastics used in the previously reported work did not include PVC. Since sources of mixed waste plastics may sometime contain PVC, it was necessary to determine the impact on the SLA properties.

The mixed plastic formulation listed above was first prepared. Various concentrations of PVC were then added to this mixed plastic stream that would be used to make SLA. The PVC used in this study was a rigid, pipe grade formulation obtained by purchasing and granulating 2" diameter PVC drain – waste – vent piping. Mixed plastic formulations containing 0, 2, 4, 8, and 16% rigid PVC were first dry blended in a V-shell blender, and then melt processed with high carbon fly ash (HCFA) to produce a 70% HCFA / 30% mixed plastic formulation.

The first melt processing studies were conducted using a Haake Torque rheometer, equipped with a two rotor heated mixing chamber. In Figure 4 and 5 the heated mixing chamber has been removed to show the rotors. The torque rheometer is an instrumented lab scale melting and mixing unit used to evaluate the processability of plastic formulations. Processing issues such as melt viscosity, discoloration, and off gassing can be studied at various temperatures and residence times.



Figure 4. Torque Rheometer

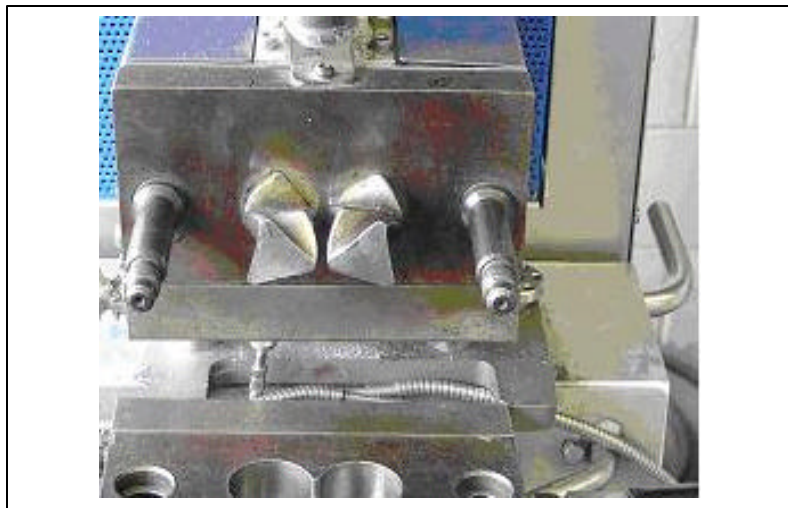


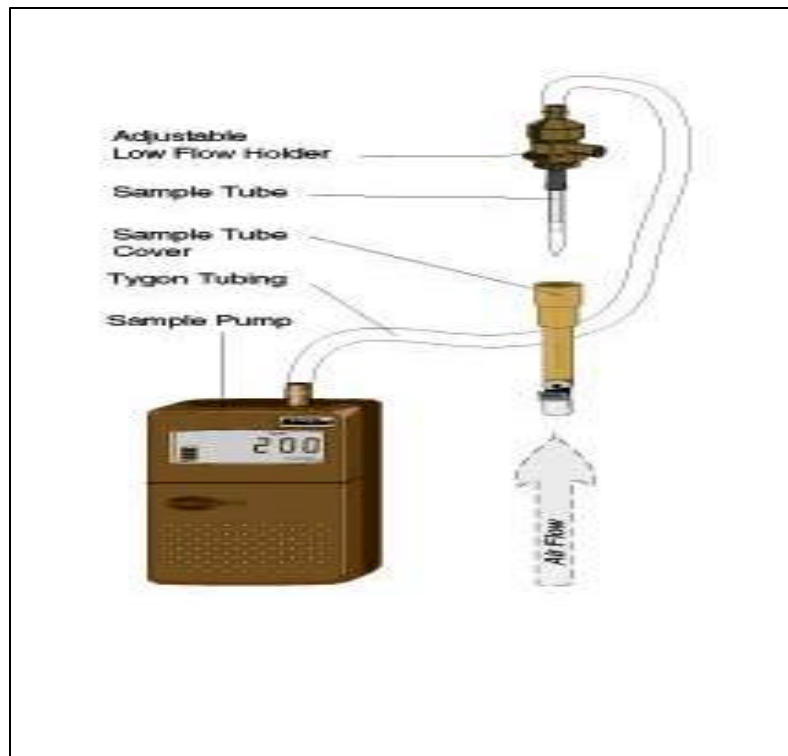
Figure 5. The Mixing Rotors

All of the tests were run at a temperature of 270°C and a rotor speed of 75 RPM. The procedure involved adding pre-weight batches of the mixed plastic formulation and fly

ash (dry and pre-blended together) into the mixer. The mixed plastic/fly ash formulations were run in the mixer for 2 minutes. The sample size was 45 grams. A 2-minute mixing time was selected as being the longest possible residence time that might be encountered in full-scale SLA production. The normal residence associated with the twin-screw SLA production is less than 2 minutes. It was clear from the beginning that significant gassing was occurring with the formulations containing 8% and 16% PVC. The off-gassing was visible and odor was significant. The formulation containing 16% PVC had also lost most of its melt flow characteristics, as observed when the mixer was opened at the end of the run and cleaned. The formulation was more solid than liquid, and very friable. It was clearly degraded and would not be useful for the manufacturing of SLA (at that high processing temperature). The formulation containing 8% PVC did still behave as a melt after two minutes of mixing but off-gassing was significant. The formulations containing 0%, 2%, and 4% rigid PVC did not exhibit any particular processing problems. No significant off-gassing or other signs of degradation were observed.

In an effort to evaluate the make-up of the off gasses that were being emitted, specifically HCL gas, analytical Dräger sorbent tubes (from BGI Inc., Waltham MA 02451) were utilized. Sorbent tube sampling is the NIOSH/OSHA approved method for collecting most hazardous gases and vapors from the air. Sorbent tubes are pre-calibrated chromatography tubes used to determine the concentration of a particular chemical present in the air. A sample is collected by opening a tube, connecting it to a sample pump, and pulling air through the tube with the pump. Airborne chemicals are trapped onto the surface of the sorbent (Figure 6) that changes the color of the sorbent in the graduated tube to a specific concentration level.

Figure 6. Dräger Tube and Pump



Tests were run at the same conditions as those described above. However, after the mixed plastic and fly ash were added to the heated mixer, an airtight cap was inserted into the mixer feed port. The evolved gasses were then drawn through HCL sensitive Drager tubes. Readings indicated that all of the formulations containing PVC resulted in significant concentrations of HCL emission. It was also determined that gasses entering the Drager tube using this technique were too hot and that the concentration levels were probably inaccurate. Additional trials were conducted where the air near the mixer was sampled and in all cases where PVC was present in the mixed plastic. HCL with concentrations of more than 100 ppmv, the maximum level detectable by the Dräger tubes, were detected in the air adjacent to the mixer.

It can be concluded that some HCL will likely be generated if the mixed plastic SLA containing PVC is run at a melt temperature of 270°C. The presence of the PVC did not appear to be a significant processing problem for SLA unless its concentration was greater than 4%. However, the fact that HCL is generated, even in small concentrations, is a concern in terms of safety and equipment corrosion. The emission of HCL gas was not unexpected since the processing temperature used for SLA is far above the degradation temperature for PVC. Although PVC constitutes a very small percentage of waste plastics from municipal solid waste stream, it would be best to strictly limit the amount of PVC used for the production of SLA and avoid its use altogether if possible. Planning for the worst case, it is recommended that any and all equipment used for SLA processing and manufacturing must be manufactured to be resistant to HCL (i.e. highly corrosion resistant alloys must be used).

5.3 Ammoniated Fly Ash Testing

All of the fly ash that was used previously for SLA studies and production has been obtained from power plants without urea based NO_x emission controls (i.e., the type that leads to the production of ammoniated fly ash (AFA)). A sample of AFA was obtained from a local coal burning utility. The exact concentration of ammonia in the sample was unknown but is typically around 100 ppmv.

In a dry state, the smell of ammonia gas volatilizing from the fly ash was barely detectable. However, when the fly ash powder was placed into a beaker of water and stirred, the smell of ammonia gas was very obvious. There was a concern that the use of AFA in a hot plastic melt (at 270°C) could also result in the release of ammonia gas. In an effort to determine if this would be the case, the Haake torque rheometer described above was used to evaluate the processing characteristics of a 70% AFA/30% mixed plastic formulation. As above, all tests were run at a temperature of 270°C for a time period of 2 minutes. During this time, air samples adjacent to the open mixing chamber were drawn with a hand pump through Drager tubes designed to detect ammonia gas.

This experiment indicated that AFA was identical to the fly ash that we had used previously in this study and that using it in the manufacturing of SLA did not impact the process. No detectable difference in viscosity, handling or odor in the vicinity was observed. The results of the Drager tube (Figure 6) tests did show that ammonia gas was

present in the air adjacent to the mixing chamber, but at very low concentrations (between 0 and 5 ppmv ammonia). Compounding extrusion trials (SLA manufacturing) were also conducted using a 30-mm twin-screw extruder. The same 70% AFA/30% mixed plastic formulation was run. Again, the process ran well with no detectable concentrations of ammonia. Drager tube air samples were taken at the extruder discharge and ammonia gas was not detected.

The last test conducted with the ammoniated fly ash was to immerse a sample of the 70% AFA/30% mixed plastic SLA prepared using the twin screw, into a beaker of water. Unlike the unprocessed AFA powder, there was no odor of ammonia when the SLA made with ammoniated fly ash was itself immersed in water. No evidence of volatile ammonia was detected by smelling or by sampling the air above the beaker with ammonia sensing Drager tubes capable of detecting in ppmv levels. This is an indication that the AFA is well encapsulated in the mixed plastic matrix.

Based on the results of this preliminary study, it can be concluded that AFA is a candidate feed material for manufacturing SLA for several reasons as long as it is dry. The AFA fly ash appears to process and perform in a manner equivalent to that of the other fly ash utilized in earlier studies. There is no evidence of significant ammonia release during SLA manufacturing.

5.4 Waste Electronic Plastics as Binder for SLA

As mentioned in section 4.2, another type of waste plastic available for beneficial use is the rigid engineered plastic used in electronics and computer housings. In order to test the hypothesis that such plastics would be appropriate for SLA production, several samples of unsorted, mixed computer waste was obtained from:

A & B Recycling
212 First Street
Fort Olgethorpe, GA 30742

The materials were supplied to us in “shredded” form, having piece sizes from 1-6 inches in length (Figure 7).



**Figure 7. Waste Electronic
Plastics**

The samples contained a variety of plastics including HIPS, ABS, and polycarbonate. The commingled shreds were contaminated with wood, paper labels, circuit boards, non-ferrous and ferrous metals (Figure 8). The total contamination was less than 5% and was removed manually.

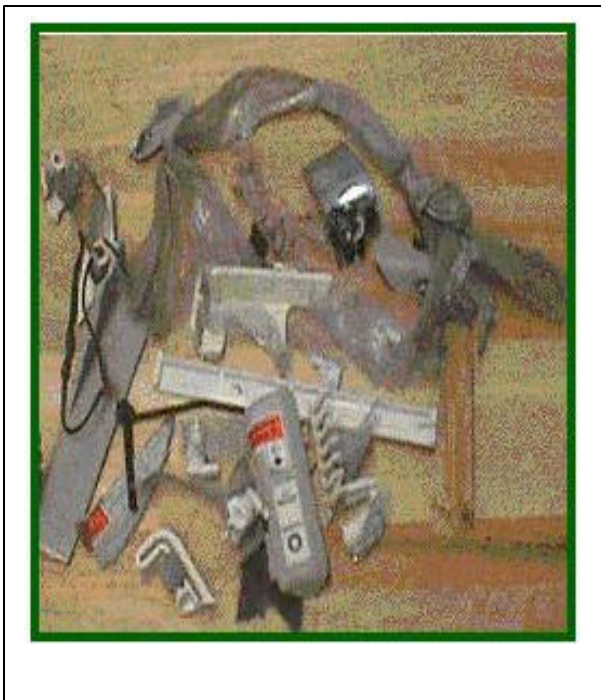


Figure 8. Contamination Present

The mixed plastic was then granulated using a rotating knife granulator with a 3/8-inch diameter screen (Figure 9). This reground material was then used as the plastic binder for 70% HCFA / 30% mixed plastic aggregate.

SLA was successfully produced using the same procedures and temperatures developed in the earlier phases of this study. Processing temperatures in the 270°C range were still used because, even though the sample did not contain PET, it did contain polycarbonate (another high melting temperature thermoplastic). No particular SLA production problems were observed other than odor problems most likely associated with the butadiene content in the HIPS and ABS fractions of the commingled waste plastic stream. However, no attempt was taken to identify the type of gas emitted from the process. It can be concluded that mixed electronic plastics can be used as the binder for SLA if most of the non-thermoplastic components are removed.



Figure 9. Pelletized Waste Electronic Plastics

6.0 ENGINEERING PROPERTIES OF SLA

The aggregate properties of the SLA investigated and reported in this section of the report (e.g., bulk density, Bulk Specific Gravity, and absorption capacity) were conducted in accordance with ASTM C128⁹ that covers the test methods necessary for measuring physical characteristics of aggregate. In addition to the SLA, two other aggregates, a normal weight aggregate (N), and a lightweight expanded clay (E) aggregate, was also tested for comparison.

All aggregates tested in this study had a nominal maximum size of 9.5 mm. The bulk specific gravity in the saturated surface and oven dry states, absorption capacity, and moisture content for all of the aggregates are presented in Table 3. The Dry rodded unit weight (DRUW) was determined for H0, C₁80H, N₁, N₂, and E coarse aggregates; the small quantity of material produced prevented the researchers from conducting the DRUW test on the remaining SLA samples.

6.1 Physical Attributes

The normal weight aggregate, N, was semi-angular with rough surface texture; the expanded clay lightweight aggregate, E, was slightly more rounded than N and had a porous appearance. The physical appearance of the SLA is dependent upon the fly ash/plastic content. Pure mixed plastic pellets have very smooth surfaces and sharp edges as the results of granulator knife cutting through the extruded plastics. SLA containing 35-50% fly ash has rounder edges and rougher surface texture resulting from a combination of the granulator cutting and breaking. The SLA samples containing 80% fly ash, have round edges, rough surface texture, and exposed small internal voids on the surface of the aggregates; the granulator breaks the extrudate to form sub-9.5 mm aggregate. The SLA samples produced and tested in this part of study are presented in Table 3.

6.2 Aggregate Bulk Density

Dry rodded unit weight (DRUW) of a coarse aggregate is used to determine bulk density values that are necessary for use in many methods of proportioning concrete mixtures. The mass of a 7080 cm³ (0.25 ft³) cylindrical metal measure was recorded. The measure was then filled to 1/3 of its capacity with oven-dried aggregate that had maintained a constant mass after being in an oven for 24 hours at 110 ± 5°C and the surface was manually leveled. The first layer was then rodded with a tamping rod 25 times, distributing the 25 strokes evenly over the surface and not allowing the tamping rod to strike the bottom of the measure. The measure was then filled to 2/3 of its capacity and the surface was again leveled by hand and vigorously rodded 25 additional times, but with no more force than to cause the tamping rod to penetrate into the previous layer of aggregate. The measure was then filled to its capacity, leveled in such a way that any slight projections of the larger pieces of the coarse aggregate approximately balance the larger voids in the surface below the top of the measure and rodded again in the manner previously mentioned. Finally, the mass of the measure and its contents was recorded.

The bulk density of the coarse aggregate was then calculated using the following equation:

$$r_{bulk} = \frac{(M_{agg. + measure} - M_{measure})}{V_{measure}}$$

Where r_{bulk} is the bulk density of the aggregate (kg/m³), $M_{agg+measure}$ is the mass of the aggregate plus the measure (kg), $M_{measure}$ is the mass of the measure (kg), and $V_{measure}$ is the volume of the measure (m³).

Table 3: Aggregate Designations for Synthetic Lightweight Aggregates

Designation	Plastic Type	% Fly Ash	Fly Ash Carbon Content	% Plastic
L50H	LDPE	50	High	50
L80H	LDPE	80	High	20
H0	HDPE	0	N/A	100
H35L	HDPE	35	Low	65
H80L	HDPE	80	Low	20
H80H	HDPE	80	High	20
P0	PS	0	N/A	100
P50H	PS	50	High	50
C50H	Commingled	50	High	50
C80H	Commingled	80	High	20
C80H	Commingled	80	High	20

6.3 Bulk Specific Gravity, Absorption Capacity, and Moisture Content

Figure 10 demonstrated the four moisture condition states for an aggregate particle. When aggregates are in the oven dry (OD) state they contain no moisture. In an air-dry (AD) condition, the aggregate may have some moisture but the saturation state was not quantified. In a saturated surface dry condition, the aggregate's voids are filled with moisture but the main surface area of the aggregate particles is dry. In the SSD condition, the voids within the aggregate are filled with moisture but the main surface area of the aggregate particle is dry. Moist aggregates have moisture content in excess of the SSD condition. Free moisture is the difference between that actual moisture content of the aggregate and the moisture content when the aggregate is in the SSD condition.

Bulk specific gravity (BSG) is the aggregate property that is used for calculation of the volume occupied by the aggregate. It is a unit-less value that compares the density of the

aggregate to that of water (1000 kg/m^3 or 62.4 lbs./ft^3). An aggregate having a BSG of 1.5 has a density equivalent to one and one-half times the unit weight of water. Values for BSG can be calculated for when the aggregate is in the oven dry (BSG_{OD}) or saturated surface dry (SSD) state (BSG_{SSD}).

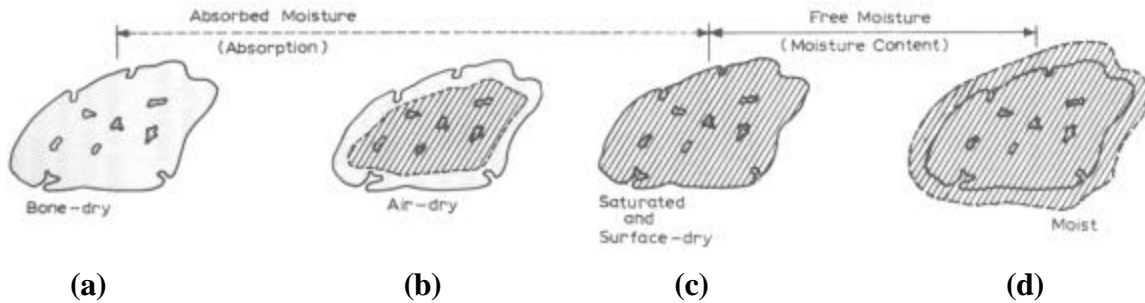


Figure 10. Voids and moisture absorption of aggregates:
 (a) OD, (b) AD, (c) SSD, and (d) moist¹².

Absorption is defined as the moisture content of the aggregate when in the SSD state. Absorption capacity values are used to calculate the change in weight of an aggregate fully saturated relative to the aggregates' weight in the dry state. Water absorbed in the pore spaces within the constituent particles must be accounted for in the mix design of a specific concrete mix, otherwise, mix water that was intended for use in the hydration process of Portland cement is no longer available and the resulting batch may not resemble what was initially intended.

6.3.1 Test Results

The bulk specific gravity in the saturated surface dry condition, BSG_{SSD} were determined per ASTM C128 and are provided in Table 4. BSG_{SSD} for the manufactured synthetic aggregate increase with an increase in fly ash content, as can be seen in Figure 11. E and all synthetic aggregates had BSG_{SSD} values less than 2.2, thus satisfying the requirements specified in ACI 213R-87 as lightweight aggregate. An aggregate having a higher BSG_{SSD} is synonymous with a denser aggregate. The increase in density is to be expected when considering that the specific gravity of fly ash is generally 2.2-2.8¹³ and the specific gravity of plastics typically range from 0.90-1.37¹⁵; the specific gravity of fly ash is approximately twice that of plastic.

SLA density is also a function of the type or types of plastics and fly ash used in the manufacturing of the aggregates. The plastics used in the production of the aggregates all had slightly different densities. However, for aggregates having identical fly ash to

Table 4: Material Properties for Coarse Aggregates

Coarse Aggregate	Material Property				
	BSG _{SSD}	BSG _{OD}	AC(%)	MC(%)	DRUW (kg/m ³)
P0	1.05	1.04	0.55	-0.35	- ^a
P50H	1.22	1.19	3.03	-2.55	- ^a
L50H	1.15	1.11	3.95	-3.60	- ^a
L80H	1.38	1.29	6.27	-5.44	- ^a
H0	0.91	0.9	0.34	-0.12	490.2
H35L	1.09	1.07	1.17	-0.98	- ^a
H80L	1.64	1.35	20.78	-7.50	- ^a
H80H	1.41	1.18	19.63	-6.61	- ^a
C₁50H	1.24	1.23	1.01	-0.66	- ^a
C₁80H	1.51	1.41	6.64	-4.11	776.9
C₂80H	1.41	1.32	6.94	-5.86	- ^a
N	2.66	2.62	1.40	-1.30	1544.1
E	1.56	1.41	10.86	-9.74	799.3

^a Properties not determined

plastics ratios but different fly ash source and plastic types, there was no significant difference in the density of the final aggregates. L80H, H80L, H80H, C₁80H, and C₂80H had similar bulk specific gravity values compared to E; as expected, N₁ and N₂ (normal weight aggregates) had the highest bulk specific gravity.

Another point of interest deserving of an investigation was the difference between the bulk specific gravity value for H80L and H80H. Both aggregates contain 20% HDPE and 80% fly ash, but differ only by the carbon content present in the fly ash (one fly ash source has a low carbon content, the other has a high carbon content). The specific gravity of fly ash is generally 2.2-2.8; the specific gravity of free carbon ranges from 1.9 to 2.3. Based on the fact that free carbon is less dense than typical fly ash, synthetic aggregates containing plastic and high carbon fly ash would most likely have a lower specific gravity than aggregates produced with the identical fly ash/plastic ratio using low carbon fly ash.

The absorption capacities, AC, were determined per ASTM C128 and are presented in Table 3. Absorption capacities for the manufactured aggregates increase with an increase in fly ash content, as can be seen in Figure 12. Aggregate samples containing no fly ash had very similar absorption capacities since pure plastic doesn't typically absorb considerable amounts of water. Lower fly ash content SLA samples have very low absorption, similar to that of the normal density aggregates, N₁ and N₂. L80H, C₁80H, and C₂80H had virtually identical absorption capacities as well. H80H and H80L had exceptionally high AC's in excess of the expanded clay lightweight aggregate, E.

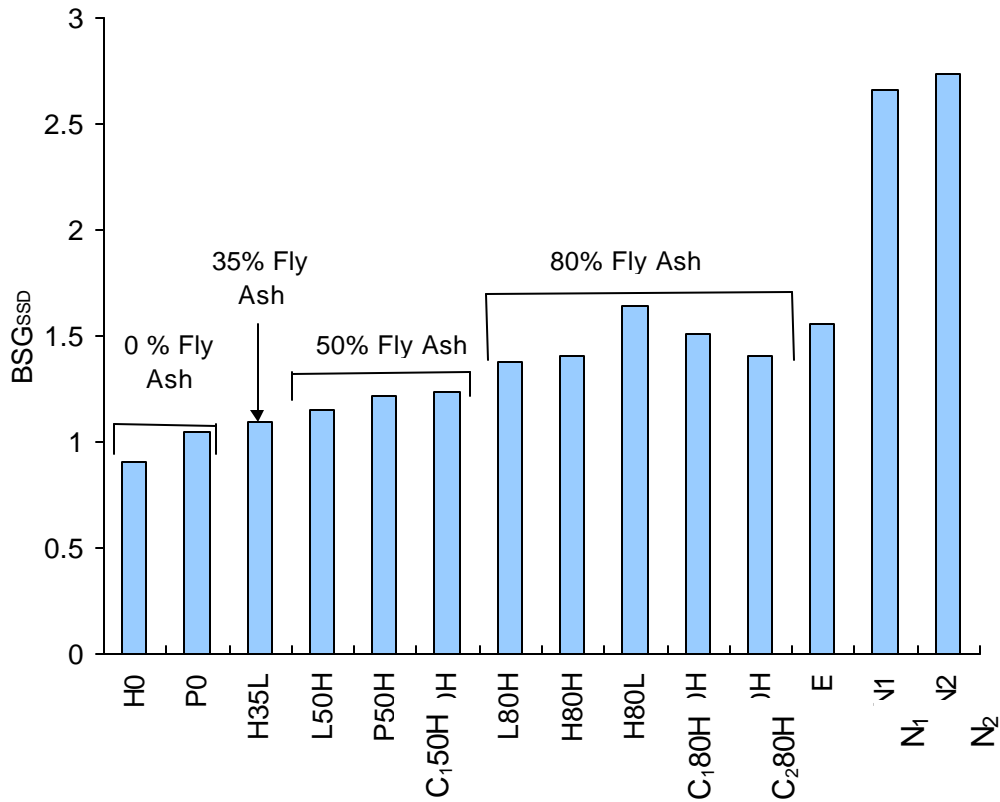


Figure 11. BSG_{SSD} for SLAs

Higher water absorption values for the SLA are indicative of high porosity that is associated with the incorporation of high volumes of fly ash into the plastic matrix. There does not appear to be a trend for increasing or decreasing absorption capacity with respect to the plastic type used within the aggregates having identical fly ash/plastic composition.

6.4 Los Angeles Abrasion Test

The Los Angeles Abrasion Test was conducted in general accordance with ASTM C131¹⁵ to evaluate the aggregates' toughness and abrasion resistance. In addition to the SLA, two other aggregates, a normal weight aggregate (N) and a lightweight expanded clay aggregate (E) were also tested for comparison purpose. The volume of aggregate used in each test was held constant for comparative purposes. Samples consisted of 5000 ± 10 g of aggregate and were adjusted relative to their BSG to generate sample sizes having equal volumes of aggregate.

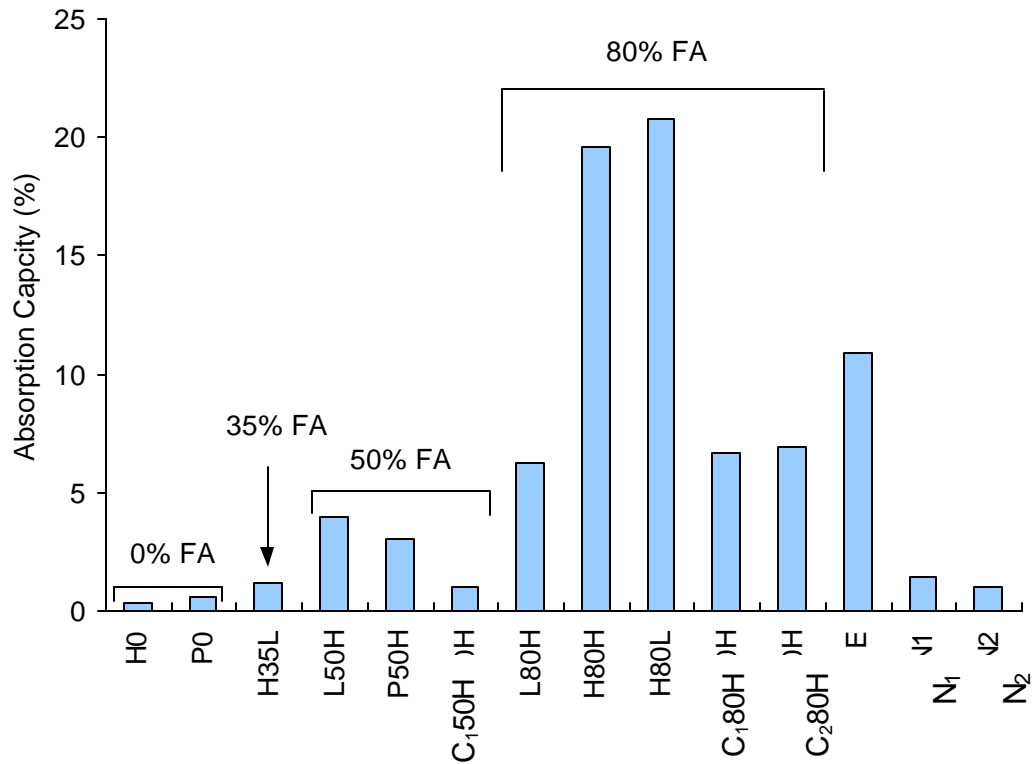


Figure 12. Absorption capacities for SLAs

The actual gradation of coarse aggregate used for the test resembled that of Gradation D indicated in Table 1 of ASTM C 131. The number of steel charges to be used is governed by the grading of the coarse aggregate. Section 6.4.1 of ASTM C131 dictates the use of six steel charges. The mass and diameter of the charges used are shown in Table 5, which satisfied the requirements stated in the ASTM C131.

Table 5: Los Angeles Abrasion Charge Diameters and Masses

Charge #	Diameter (mm)	Charge Mass (g)
1	46.863	417.1
2	46.914	417.3
3	46.888	417.5
4	46.863	417.1
5	46.965	417.7
6	46.863	416.9
Total Mass of Charges		2503.6

The samples were washed and then oven dried to a constant mass at $110 \pm 5^\circ\text{C}$. The test sample was then placed into the Los Angeles testing machine along with the six steel charges, as shown in Figure 13. The machine was then rotated at a speed of approximately 32 revolutions per minute for 500 revolutions. The material was then removed from the testing apparatus and preliminarily separated using a No. 8 sieve (2.36 mm spacing). The finer portion was then sieved through a No. 12 (1.70 mm) sieve. The material coarser than the No. 12 sieve was then oven dried to a constant mass at $110 \pm 5^\circ\text{C}$. The mass of the oven-dried material was then measured and recorded, and the Los Angeles Abrasion Number was calculated using the following equation:

$$LA \text{ Abrasion Number} = \left(\frac{M_{sample(original)} - M_{sample(coarse)}}{M_{sample(coarse)}} \right) (100\%)$$

where $M_{sample(original)}$ is the total mass of the original sample (g) and $M_{sample(coarse)}$ is the coarse portion of the aggregate larger than the No. 12 sieve (1.77 mm) after 500 revolutions.

The LA Abrasion Test was conducted on three coarse aggregates; N₁, E, and C_{280H}. LA Abrasion #'s were calculated using the above equation and the values are presented in Table 5.

Table 6: LA Abrasion #'s for the Coarse Aggregates

Aggregate	LA Abrasion #
N	14.8
E	27.9
C _{280H} SLA	6.6

6.4.1 Test Results

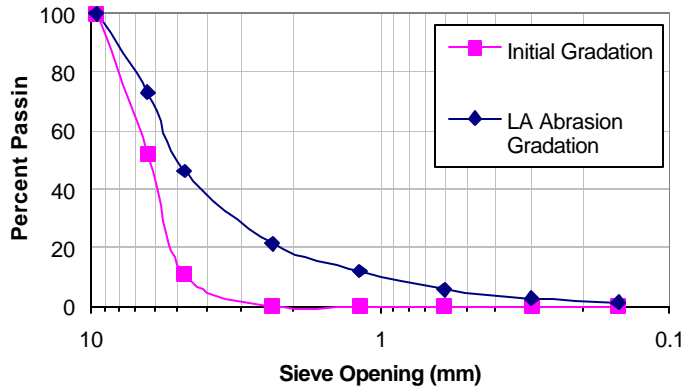
The Los Angeles Abrasion test results are presented in Table 5. The tumbling and dropping of the aggregates along with the steel charges resulted in abrasion and attrition of the aggregate. The expanded clay lightweight aggregate, E, performed poorly as compared with the other two samples, as can be seen from the comparison between the initial gradation and gradation after the LA Abrasion test presented in Figure 14(a);

The normal density aggregate, N, performed quite well; the dense structure of the aggregate is relatively resistant to abrasion and effective in absorbing energy dissipated during impact with the steel charges. A comparison between the initial gradation and gradation after the LA Abrasion test for N is presented in Figure 14(b) and shows how the fines content increases.

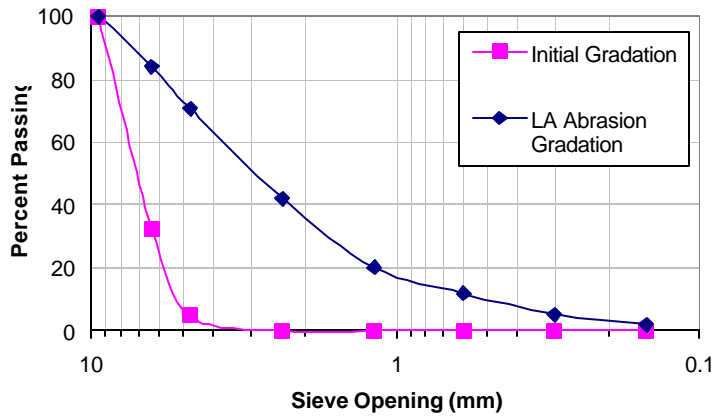


Figure 13. Los Angeles Abrasion test machine

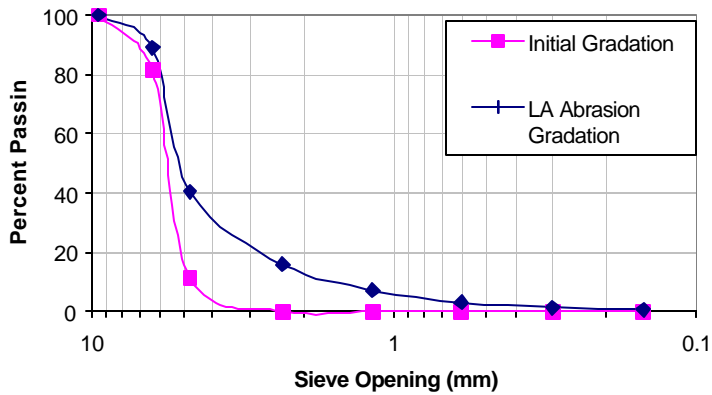
Most impressive is the performance of the SLA made with 80% fly ash and 20% mixed plastics. Having the lowest LA Abrasion value of the three aggregates investigated, the SLA is very effective in resisting abrasion and impact. The high porosity associated with a high volume fly ash aggregate would lead one to expect poor performance, as is the case with E. Contrary to what might be expected, the SLA has exceptional energy absorption capabilities. Izod impact tests previously performed on the SLA specimens indicated that SLA is a very effective material for absorbing energy dissipated through impact. A comparison between the initial gradation and gradation after the LA Abrasion test for the SSLA sample is presented in Figure 14(c). The fines content has increased, although the increase was minor relative to N and E.



(a) N



(b) E



(c) SLA

Figure 14. Initial aggregate gradation and gradation after the LA Abrasion Test for (a) N, (b) E, and (c) SLA

7.0 CONCLUSIONS

This study investigated the development of synthetic lightweight aggregate (SLA) from two types of waste materials routinely sent to landfills. We studied the effect of PVC in the production of SLA and used waste plastics from electronic industry to produce SLA. We also investigated use of ammoniated fly in SLA. A large quantity of SLA was produced and tested for engineering properties such as bulk specific gravity, absorption, bulk density, and Loss Angles Abrasion loss. The conclusions are as follows:

1. Some HCl will likely be generated if the mixed plastic contains rigid PVC and is processed at a melt temperature of 270°C. The presence of the PVC did not appear to be a significant processing problem for SLA unless its concentration was greater than 4%. However, the fact that HCL is generated, even in small concentrations, is a concern in terms of worker safety and equipment corrosion. It would therefore be best to strictly limit the amount of PVC used for the production of SLA and avoid its use altogether if possible. Planning for the worst case, it is recommended that any and all equipment used for SLA processing and manufacturing must be manufactured to be resistant to HCL (i.e., highly corrosion resistant alloys must be used).
2. Based on the results of this preliminary study, it can be concluded that ammoniated fly ash (AFA) is an acceptable candidate feed material for manufacturing SLA as long as it is dry. The AFA fly ash appears to process and perform in a manner equivalent to that of the other fly ash utilized in earlier studies. There is no evidence of significant ammonia release during SLA manufacturing.
3. SLA was successfully produced with waste plastics from electronic industry using the same procedures and temperatures developed in the earlier phases of this study. No particular SLA production problems were observed other than odor problems, most likely associated with the butadiene content in the HIPS and ABS fractions of the commingled stream. It can be concluded that mixed electronic plastics can be used as the binder for SLA if most of the non-thermoplastic components (metal, paper, etc.) are removed.
4. The bulk specific gravity and absorption capacity of the SLA generally increase as the fly ash content of the synthetic lightweight aggregate increases.
5. The SLA made with 80% fly ash had the lowest LA Abrasion # compared to the expanded clay and normal weight aggregates. Its superior performance is attributed to the energy absorptive properties of the plastic present in the aggregate.

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